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PROCEEDINGS OF THE FIRST CONFERENCE ON THE ENVIRONMENTAL EFFECTS OF EXPLOSIVES AND EXPLOSIONS (MAY 30-31, 1973)

George A. Young

Naval Ordnance Laboratory
White Oak, Maryland

12 February 1974

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This report is a compilation of papers presented at the First Naval Ordnance Laboratory Conference on the Environmental Effects of Explosives and Explosions. The topics covered included the manufacture of explosives and weapons; the testing and use of explosives in the air, ground, and water; and the disposal of scraps, wastewater, and large items of obsolete ordnance. Physical, chemical, and biological effects of both nuclear and conventional explosions were treated.

SUMMARY

NOLTR 73-223 **12 February 1974**

Proceedings of the First Conference on the Environmental Effects of Explosives and Explosions (May 30-31, 1973)

As the general field of study of environmental and ecological problems related to the manufacture and use of explosives is developing rapidly, and much of the research is new and is not widely known, it was decided that the needs of the Department of Defense and other organizations for current information could be met most effectively by the scheduling of a conference. This conference, the first of its kind, was sponsored by the Naval Ordnance Laboratory to provide a forum for workers from government, industry, universities, and research laboratories.

The Proceedings published here constitute a summary of the present state of knowledge of topics such as the effects of explosions on marine life and birds, the environmental effects of Deep Water Dumps and other methods of disposal, pollution abatement in explosive manufacture, the environmental effects of underwater demolition, and the purification of wastewater from TNT factories. In addition, the extensive Army and Navy programs related to pollution abatement in explosive production and handling are thoroughly described.

The papers are summaries of the talks, together with prints of the important slides. In some cases, only an abstract is available, and in others, a reference to a recent publication covering similar material is provided.

The preparation of this report was supported by the Naval Ordnance Systems Command under Task ORD-332-005/UF 53-554-301, titled "Environmental Effects of Explosive Testing."

ROBERT WILLIAMSON II
Captain, USN
Commander

I. Kabik

I. KABIK
By direction

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KEYNOTE ADDRESS

by

J. A. D'Emidio, Captain, CEC, USN Director
ENVIRONMENTAL PROTECTION DIVISION
OFFICE OF THE CHIEF OF NAVAL OPERATIONS

Thank you for this opportunity to open this Conference on the Environmental Effects of Explosives and Explosions. I am particularly sensitive to this area because one of the first environmental concerns we had with the creation of OP-45 in late 1970 were the problems associated with the CHASE Dump operations.

In those days because of the chemical dump operation, the oil spill problems and for other reasons, our relationship with the CEQ/EPA and environmental groups were strained. A dialogue has been established and we are now confident that our relationships will improve significantly through our mutual understanding, improved operational procedures and the evolution of new technology with respect to munitions handling, processing, and disposal.

As regards our actions, I recognize that it is difficult to satisfy the many environmental groups on all points, because they have varying goals and standards.

The disposal of obsolete and unserviceable munitions has been practiced by most coastally located nations for many years; and except for the U.S. and Canada, this method of disposal continues to be practiced by many nations.

The U.S. would have continued the disposal of ordnance into the sea program, except that a few unfortunate situations developed in that period of time.

First, we got involved with the Army chemical warfare agent disposal off the coast of New Jersey. The public, press, and political outcry was unbelievable.

Also, in October, the Council on Environmental Quality released the National Policy on Ocean Dumping. This policy recommended that ocean disposal of chemical and biological warfare agents be prohibited and that disposal of explosive munitions by this means be phased out.

The Navy prepared a Draft Environmental Impact Statement so that ordnance material could be dumped--but the public outrage and the political pressures made even the filing of the DEIS for consideration and comment, not prudent.

In February, the then Secretary of the Navy John Chaffe, decided to suspend all deep water dumping of obsolete and unservicable munitions until all alternative methods of disposal are completed. The Secretary of Defense Melvin Laird approved of these measures.

Two actions were immediately initiated:

(1) A study of all new munitions designs to ensure that a demilitarization capability is built into them at the time munitions are manufactured; and

(2) Secondly, the Oceanographer of the Navy was requested to:

(a) Acquire, through environmental studies, ecological and oceanographic information to enable the preparation of comprehensive environmental condition reports on representative past deep water disposal sites,

(b) Develop criteria for selection of future disposal sites should such action become necessary; and

(c) Determine what monitoring efforts will be required for future sites.

I am pleased that the information at this conference will address many of these issues and discuss the results of studies conducted.

There is one other aspect of this problem that I would like all of you to give serious consideration as we consider the future environmental effects of conventional ordnance. Namely, the National Environmental Policy Act.

The National Environmental Policy Act of 1969 is one of the most all eccompassing laws with respect to the environment and requires Federal agencies to build into their mainstream of management decision making process, down to the lowest level of the organization, an awareness of environmental factors at the very inception that plans and programs are formulated, any Federal action which may have a significant impact on the human environment or which may become highly controversial require environmental impact statements to be filed with the Council on Environmental Quality. I know that some ordnance testing/processing, etc. is being conducted without having completed such an assessment covering all facets of environmental affects and viable alternatives. A recent test involving the explosion of a 500 pound bomb in a marine environment inhabitated area, was being planned without environmental impact assessment considerations, until our office became involved. Such actions . . in violation of the law and our instructions.

The additional administrative burden and expenditure of funds occasioned to date and to be expected in the future is regrettable. However, the Navy has an obligation to comply with NEPA and other applicable laws especially when accelerated by court actions. The Navy's program to implement the National Environmental Policy Act (NEPA) and CEQ Guidelines requires assessments at the very initiation of any planning covering the myriad of decisions being made on a daily basis throughout the Navy. Consideration of environmental factors must be a way of life for managers in the chain of command and must complement the assessment of other requirements needed in decision making, such as mission, functional, cost effective, technical, etc., to eventually effect the long term goals of NEPA and Navy instructions (OPNAVINST 6240.2C).

The Navy has submitted 22 Environmental Impact Statements and we currently have in process at least 15 more. The CNO Environmental Impact Assessment Board has reviewed over 112 Candidate Impact Assessments which were judged not to require the filing of an Environmental Impact Statement.

We were taken to court in four instances based on the law:

(1) Target Range, Kahoolawe, Hawaii

(2) Training Exercise, Reid State Park, Maine

(3) Project SANGUINE

(4) Family Housing, Groton, Connecticut

Navy won all cases.

You will note that the first two cases involve training, and especially Navy targets. This area is one that is extremely sensitive to environmentalists and requires the most stringent examination possible. One area of knowledge that is lacking, hopefully to be discussed at this conference, is exactly what ordnance explosive contaminants are released as the result of our training, especially as regards air-to-ground and ship-to-ground exercises. How do these toxic materials if any, find their way into the food chain and for how long? We are being asked these questions today and do not, at least to my knowledge, have the answers.

The passage of strict national pollution abatement laws coupled with the Federal mandate directed by Presidential Executive Orders has created a serious impact on naval operations in all environments; land, sea, and air. Therefore, th Navy's financial commitment to meet existing and evolving environmental standards and regulations far exceeds that of all other Federal agencies. In all areas of environmental concern our budget has grown from $60 million in FY 72 through $140 million in FY 73 to $224 million in FY 74. We intend to support environmental efforts under the ordnance umbrella.

I wish to thank you again for this opportunity and to wish you a highly professional and successful conference.

Talk Presented By

Daniel J. Quagliarello
Logistics Support Directorate
Naval Ordnance Systems Command

At

Conference On The Environmental Effects
Of Explosives and Explosions
30-31 May 1973

Naval Ordnance Laboratory
White Oak, Silver Spring, Maryland

NAVAL ORDNANCE RDTE PROGRAMS POLLUTION ABATEMENT

The area I will cover today is that of Ordnance Pollution Abatement. The work in this area is currently proceeding on three major fronts:

(1) Designing future ordnance to be compatible with rapid disposal techniques.

(2) Developing processes for the disposing or recycling of explosives, propellants and pyrotechnics and

(3) Improving the methods and techniques used in the deep sea disposal of ordnance.

NAVORD facilities explosive load a large variety of ammunition for both the Navy and the Air Force. Manufacturing techniques associated with explosive loading result in pollution in the form of dust and contaminated water. Disposal of reject material from explosive loading, propellant manufacturing and demilitarization operations is an enormous problem as indicated by the following slides.

As of 30 October 1972, A total of 88,000 tons of propellants and explosives were available for disposal. Each year, thousands of tons of scrap or reject propellants and explosives are burned in the open air.

In the past the Navy has disposed of its waste ordnance and related hazardous materials by the most expeditious means available, such as deep water dumping, detonation, controlled incineration, explosive washout and open burning. Ocean dumping has been halted by the SECNAV imposed ban on ocean dumping of ammunition and other dangerous materials.

Detonation creates air and noise pollution whereas controlled incineration which is conducted in large deactivation furnaces and is confined to small arms, primers, detonators, fuzes and other small explosives, creates smoke and gases resulting in air pollution. Large items such as mines are demilitarized by explosive washout which allows reclamation of the explosive but also generates contaminated water which pollutes the environment. While open burning is still permitted in many localities, we know that future disposal methods will have to comply with recently enacted legislation for the protection of the environment. In view of the Navy's continuing mission in ordnance operations such as propellant manufacturing, demilitarization and explosive loading, alternative methods of degradation and disposal must be developed.

In the following discussion, I will treat both short term and longer range solutions concentrating mainly on the problems associated with the degradation and disposal of reject or overage solid propellants both in the as manufactured state and as incorporated in missile propulsion units.

However, before talking about solutions, let us first glance very briefly at the components of these hazardous materials and how they pollute the environment when disposed of improperly. As the following slide shows, most solid propellants and explosives contain materials such as HMX, RDX and various lead salts that are toxic in themselves. Keeping these materials from introduction into the environment during processing and disposal operations is of prime concern to the Navy. When these hazardous materials are disposed of by open burning, further pollutants are released to the atmosphere in the form of toxic gases, while the lead and copper salts remain in the soil and eventually reach the water table.

Exhaust systems and scrubbers and now being installed at many of our explosive loading facilities that will safely and efficiently remove dusts and fumes and will significantly reduce contamination of streams.

Recent process innovations introduced at NAD Crane in flare disassembly allow us to reclaim magnesium and sodium nitrate for future use. The reclaimed magnesium can be reused or sold and the sodium nitrate can be used as fertilizer.

A liquid incinerator has been operational at Cape Kennedy burning Otto Fuel contaminated liquids for the last nine months. Solid incinerators are programmed for sub-base New London, WPNSTA Charleston, NAD OAHU and NAVTORPSTA Keyport. Liquid disposal contractors have been identified for the sub-base New London area and NAD OAHU. A liquid incinerator has been installed at NAVTORPSTA Keyport. It is planned to have all mentioned Otto Fuel incinerators installed and operational by the end of 1973.

A box incinerator for disposal of small ammunition items has been designed with pollution abatement features and is in the purchasing process by NAD Crane. Emmission tests recently completed at Crane have resulted in proposed demil furnace modifications which will include bag filters for particulate removal and prototype wet scrubbers for fume reduction verification.

Manufacturing technology efforts are underway at WPNSTA Yorktown to develop recycling systems for contaminated water generated during explosive washout operations. Flaking units used in conjunction with such recycle systems will yield additional reclaimed explosives which can be reused or sold. A pictorialized schematic of a 3" projectile washout system with the filtered water recirculating feature for explosive recovery is shown.

Also in the area of reclamation recent studies at WPNSTA Yorktown have proven that the explosive HBX can be steamed out of munitions and conventionally flake dried to yield a product that might be commercially saleable. It is anticipated that this process will be scaled to a demonstration plant size within the next 6 to 12 months.

My discussion thus far has been oriented to solutions that are considered state-of-the-art". However, NAVORD also conducts research and development as well as manufacturing technology efforts that are directed toward novel, long range or more cost effective solutions to ordnance pollution abatement. It is anticipated that within the next few years one or more of these advanced systems will assume the bulk of the workload for the disposal and reclamation of ordnance.

The first of these advanced systems I wish to discuss is known as the wet air oxidation process. Extensive engineering effort has been expended during the past two years to develop design criteria for a plant to dispose of reject or overage solid propellants using the wet air oxidation process. The wet air oxidation process which in the past has been used to degrade a large variety of materials, offers a safe low temperature method for the destruction of waste propellant and explosive materials.

The wet air oxidation principle is quite straight forward. The heart of the process is a high pressure reactor. A stream of air and a slurry of propellant (about 10% in water) are continously fed to the reactor. The reactor is maintained at a pressure of 600 - 1000 psi and a temperature of 200°C.

Additional equipment for the process consists of a propellant waste slurry system, a high pressure pump for injecting the slurry into the reactor, an air compressor, heat exchangers, an effluent cooler, a separator, and an oxidized product receiving tank.

The major combustion products of single and double base propellants are CO_2, CO, water, nitrogen,nitric acid and metallized salts from aluminum and burning rate modifiers. However, nitrous oxide, nitrogen oxides and hydrocarbon gases are also produced. The gaseous effluent from the system will be sent through an afterburner to oxidize the CO to CO_2 and a scrubber to reduce the nitrogen oxides to less than 40 ppm. The water phase can be treated with ammonia to convert the approximately 1% nitric acid solution to ammonium nitrate and to remove the metals such as lead, which may be present. The resulting ammonium nitrate solution can be concentrated to about 20% by reverse osmosis and used for fertilizer. The effluent, dilute ammonium nitrate solution (0.01%), will be recycled to the oxidation system.

There is no flame during the oxidation process. The energy released by the oxidizing propellant is absorbed by the water and serves to maintain the temperature of the system.

Wet air oxidation destroys the propellant grain and produces a dilute nitric or hydrochloric acid solution depending on the type of propellant processed.

NAVORDSTA Indian Head, working together with industry, has adopted two prototype wet air oxidation units for the disposal of solid propellants.

The first of these devices can process a continuous feed of 5 to 10 pounds per hour, while the second prototype will process 50 to 100 pounds per hour. Data generated from these prototype developments will be used to design and fabricate a 500 pound per hour plant. This plant is expected to be operational at NAVORDSTA Indian Head within the next 12 months.

The second technique under consideration by the Navy is the fluidized bed process.

Picatinny Arsenal is currently funding the ESSO Research and Engineering Company to perform laboratory-scale experimental fluidized bed incineration of HMX, RDX, TNT and other explosive materials. NAVORDSTA, Indian Head is presently negotiating a contract with Fluidhearth for bench scale studies on sold propellants using the fluidized bed process.

A third technique under study for ordnance disposal is the Molten Salt Process. In this process the waste propellant is combusted in a pot of molten salt. The pot typically contains an alkaline metal salt mixture at a temperature up to 1800°F. The function of the alkaline metal salt mixture is to catalyze the combustion as well as neutralize the acidic gaseous pollutants. The heat generated in the combustion process can be recovered for process use or for electricity generation. Acidic gases and ash are trapped in the salt mixture, while the combustion products are sterile and odor free.

NAVORD is currently funding Atomics International for a one year pilot study to determine the feasibility for disposing of explosives and propellants safely and in a non-polluting manner using the Molten Salt Process. During the course of this program, 5 explosives and 6 propellants will be screened for compatibility with the Molten Salt Process. In tests already performed on the disposal of the explosive composition B, no detonations occured with up to one pound samples when operating the reactor at 1800°F. It was determined in this initial portion of the study that optimum combustion of the composition B took place on the surface of the melt and at a temperature of approximately 1400°F. Upon the successful completion of these feasibility tests, operating and capital costs for construction of a full size disposal unit will be generated.

The use of biodegradation as a means of disposal for propellant and explosive wastes has thus far received only minimal consideration. Laboratory efforts within NAVORD are being conducted at the Naval Weapons Center, China Lake, and the Naval Ordnance Laboratory, White Oak. The China Lake effort is general in nature and is designed to determine which organisms give the greatest percentage biodegradation of explosives when these organisms are exposed to dilute solutions, suspension in water and solid material.

Initial work at China Lake has been confined to investigating possible methods for biodegrading RDX and HMX. A contract has been let to the

Ecological Systems Corporation of Santa Monica to assist in this study. The technical effort expended to date has failed to uncover any bacteria capable of attacking and breaking down RDX and HMX. NOL White Oak is more specific in that its end goal is to find an efficient biological process for destroying TNT in waste water. Thus far, three bacterial isolates have been shown to actively metabolize TNT, but only in the presence of additional nutrient, such as glucose. The rate of TNT biodegradation using bacteria from activated sludge has been measured at up to ≈4 ppm TNT per hour. A research pilot plant for the biodegradation of TNT at NOL has been designed, and when in operation will have the capacity to biodegrade up to half a pound of TNT per day.

A preliminary study at NAVORDSTA Indian Head was conducted to determine if the liquid monopropellant, Otto Fuel II, could be biodegraded. Initial results indicate that this would be a feasible approach to break down at least certain constituents of the Otto Fuel.

While the three processes I have just covered are the major methods under consideration within NAVORD for propellant disposal, there are several other techniques that deserve at least a brief comment. One possibility under study is based on the observation that fire storms are very efficient incinerators. In work being done at the Illinois Institute of Technology, fire storms have been simulated in a very simple way by the installation of verticle louvers. Once established, the flame column is relatively stable. Air is sucked in at a rate that contains the column and appears to maintain stoichiometric burning throughout the column with significant reduction in smoke.

A second possibility under discussion is an extension of the technology available in the field of rocket propulsion. In this process, the propellant waste material is first water slurried and then pumped into the reaction chamber. Propane, used as a pilot light to ignite the reaction, will be pressure fed from a commercial source. Gaseous oxygen, required in addition to the oxidizer available in the propellant, will also be pressure fed into the combustor. The use of oxygen, rather than air, significantly reduces the volume of the combustion chamber and associated gas scrubbing system, insures a higher combustion temperature and reduces the formation of nitrogen-oxygen compounds.

The rocket combustor is essentially a small water-cooled rocket engine operating at 100 psia chamber pressure, and temperatures ranging from 3000 to 5000°F. The waste and propane are burned with gaseous oxygen in the combustion chamber.

In the preceding discussion of the various processes for propellant disposal currently being investigated by the Navy, we have assumed for each method that the disposal material is already available in a convenient form. For efficient disposal, the waste materials must be reduced to a uniformly small size.

If the materials are not already in a reduced size, such as reject casting powder, it will be necessary to employ an array of size reduction equipment to achieve a final particle size acceptable to the disposal method. In the case of the wet air oxidation plant scheduled for installation at NAVORDSTA, Indian Head, this maximum particle cross-section is one-quarter inch. To accomplish this size reduction necessary to all propellant disposal methods under consideration, NAVORD facilities are evaluating a variety of equipment. Six types of size reduction units under consideration are: Attrition Mills, Knife Grinders, Crushers, Dicing Machines, High-Pressure Water Jets, and Ball Mills. All of these differ in their method of reduction. The Attrition Mills, Knife Grinders, Crushers, Dicing Machines and Ball Mills are all mechanical in nature, and are generally applicable only to certain classes of materials and for achieving specific sizes. In most cases, before materials can be fed into one of these machines, the propellant grains must first be sawed or milled out of their containers. A safer technique for performing this operation, known as the Hydro Jet, is currently undergoing a pilot scale evaluation at NAVORDSTA, Indian Head for reclaiming the cases from the tartar and sidewinder rocket motors. In this technique high-pressure water jets impinge on the propellant grain which causes it to crumble by an eroding action. The propellant chunks and water are received in a catch tank making possible the recycling of the water.

A final comment on propellant disposal concerns the Navy's program in deep water disposal. As I mentioned in the beginning of this presentation, deep water dumping has been stopped. For the past two years, NAVORD and the Oceanographer of the Navy have been actively engaged in a survey of past deep water dumping sites.

The following series of slides were generated from this survey. They are pictures taken of the sea bottom five years after an explosive hulk was sunk and detonated at a deep water dump site (not printed).

While all questions about the environmental effects of past deep water dump operations could not be answered by the present program, the results indicate that this disposal method does not do significant irreversible damage to the deep ocean environment. The Navy feels that this tool should be evaluated carefully against the potential hazards and costs, as well as ground, air and stream pollution which may be connected with future Terrestrial Ordnance Disposal Systems. With care in site selection and intensive operational control, deep water dumping is available and environmentally defendable alternative method of Ordnance Disposal. There is still extensive discussion of the problems of ocean disposal among the federal agencies in Washington and a task force on dumping criteria has been organized. Naturally the Navy has a priority interest in these discussions. As a large user of radioactive material and other exotic substances, we anticipate continuing rational need for such disposal. tectonic sinks offer one possible solution that may ultimately be politically acceptable. The Naval Civil Engineering Laboratory has proposed a joint venture with the atomic energy commission to investigate this approach.

In the disposal of propellants and explosives, large amounts of contaminated waste water are usually generated during the steps leading up to the final disposal operation. This problem of contaminated waste water is also common to many operations during the manufacture and fabrication of most propellants and explosives, and is planned to be alleviated through recycling systems similar to the approaches being pursued by the Army. Another possible method for handling this problem is now under study at NAVORDSTA, Indian Head. In this particular setup the problem is to remove the liquid monopropellant, Otto Fuel II, from water contaminated during the manufacturing process. The method for achieving this goal is to first collect the contaminated water in a holding tank and allow it to settle for a period of several hours. The spillover water then passes through a coalescer where the Otto Fuel contents is halved. The fluid from this stage drops into a second holding and eventually flows through a series of activated carbon columns. By passing through this simple array Otto Fuel content can be reduced by two orders of magnitude. Pilot plant studies will soon be initiated at the Naval Ordnance Station that will allow the processing of 300 gallons of contaminated water per hour. This method, and others like it, are under investigation by other laboratories for such problems as the purification of water contaminated by HMX, RDX, and TNT.

The last major segment of NAVORD's effort on the Ordnance Pollution Abatement program is that of designing future ordnance with disposability in mind. The following are programs which NAVORD is currently funding.

Stanford Research Institute is currently investigating the feasibility of developing explosive compositions with inherent disposal characteristics. From their work thus far it appears feasible to prepare heat-sensitive binders that will have sufficient stability at normal service temperatures and that can be degraded at elevated temperatures in a matter of hours without causing excessivie decomposition of the explosive.

NAVORDSTA, Indian Head is investigating this area of degradable binders with respect to solid propellants. Again, the main thrust of the effort is to identify binders that become thermally unstable at relatively low temperatures (300°F).

The Naval Weapons Center, China Lake, is attempting to develop a family of water soluble binders for explosives. Binders that are also potentially biodegradable will have preference in this investigation.

NOL White Oak has been conducting a program to prepare a number of non-polluting polynitroaliphatic substitutes for standard military explosives. The current interest in these polynitroaliphatic materials is that most of them can be manufactured and disposed of in relatively non-polluting manners.

This is because they are straight chain rather than ring compounds and are more easily broken into lower molecular weight fractions by steam or alkali.

From the standpoint of hardware, NWL Dahlgren is developing a new approach to the design of projectiles to ease substantially the job of disposing of this type of munition in a acceptable manner. The encapsulated charge, if readily removable, would eliminate the need for detonating this type of munition in the future.

a DOD responsibility, unique to NAVORD which is discharged world-wide, has been that of recovering silver for film, which in the past could be accomplished by incineration without the need for extraordinary controls on particulate emissions. A special purpose, combustion controlled incinerator capable of meeting the most stringent existing particulate emission standards, has been installed at our primary silver recovery activity in Earle, New Jersey, and is in the final checkout stages. Purchasing efforts underway as part of this program call for utilization of this improved film incineratory at nine other DOD film accumulation centers.

Investigations are also in progress at NAVORDSTA, Indian Head to determine the applicability of either wet air oxidation or Molten Salt to the silver recovery problem.

In terms of coordinating NAVORD's pollution abatement program, two efforts bear mentioning.

To collate and assimilate data derived from all Navy pollution abatement programs, the Navy environmental protection data base was established in 1972. This program is to serve the very practical purpose of collecting and converting good data into useful information for all Navy offices having a legitimate requirement for such information.

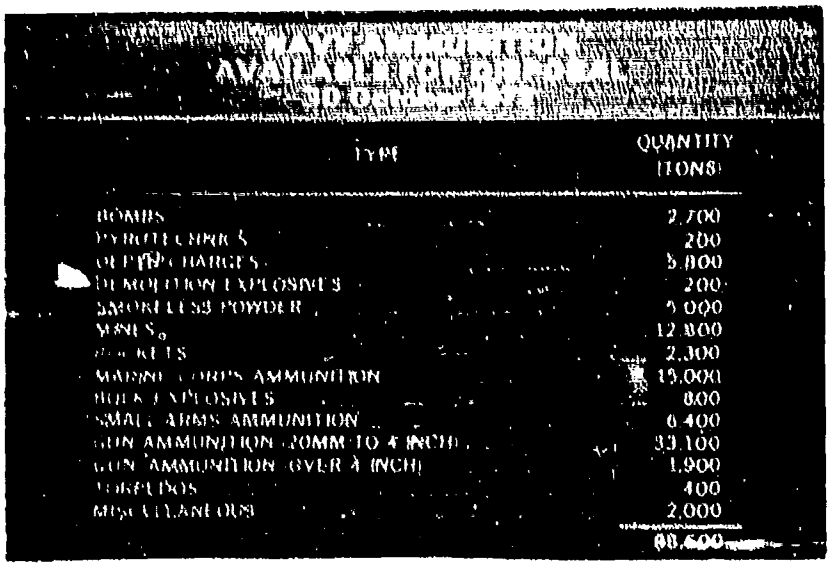
In a related pilot study, we are developing an environmental inventory at the Patuxent Naval Air Station to determine in greater detail the facts which should be collected about our shore stations to fully understand our environment.

Our future plans include:

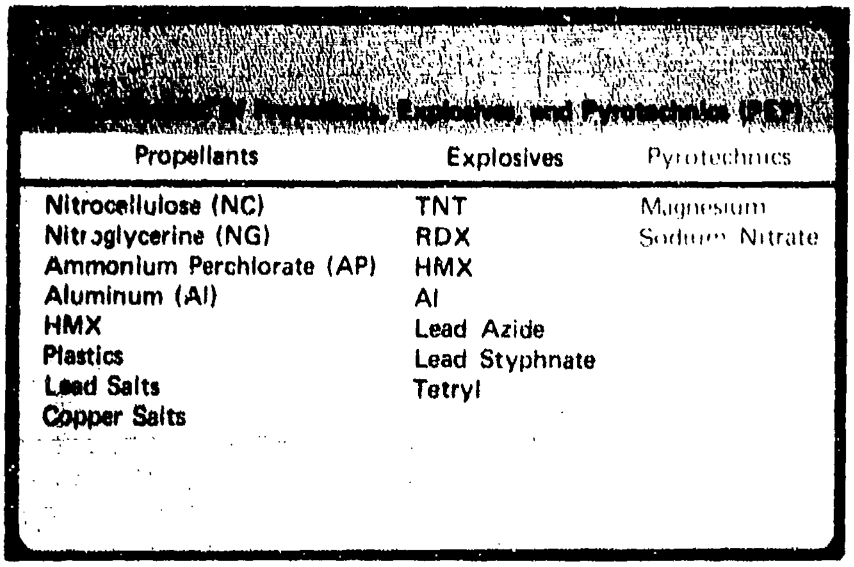
(1) Continuing to develop better methods for disposal of ordnance with emphasis upon reclamation and pollution abatement.

(2) Placing greater emphasis upon the development of new propellants and ordnance with ease of disposability, a prime design goal.

The end goal of all the projects discussed today, and the others not mentioned, is to prove that protecting the environment for the future is compatible with the Navy's primary mission of protecting the nation.



SLIDE 1



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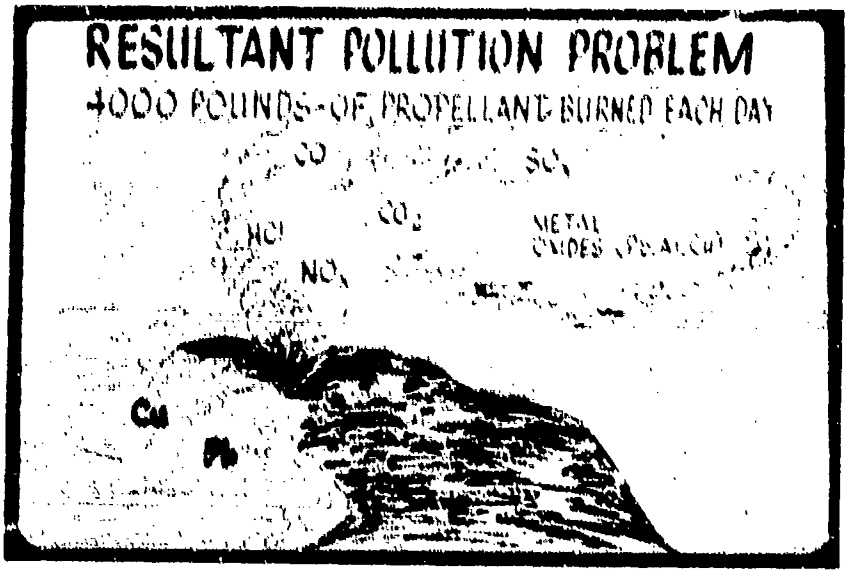

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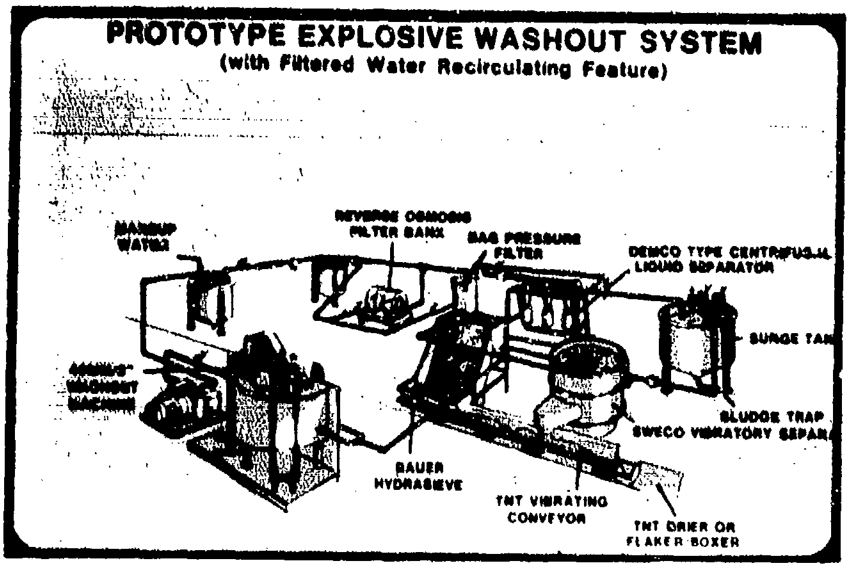

SLIDE 4

POLLUTION ABATEMENT IN ARMY EXPLOSIVES PRODUCTION

By

GERALD R. ESKELUND and ALLAN F. BURNS

ABSTRACT

Production of explosives generates several unique pollutants, often in large quantity, which require special treatment of air, water, and solids. Directions being taken for handling pollutants such as NO_x, aqueous effluents containing dissolved TNT and nitrates, and waste explosives, are discussed. The goal of the Army in pollution abatement is to close the loop on waste streams and recycle as much material as possible.

POLLUTION ABATEMENT IN ARMY EXPLOSIVES PRODUCTION

By

GERALD R. ESKELUND and ALLAN F. BURNS

Munitions Command (MUCOM), soon to be part of the new Armaments Command, has one of the largest and most unique industrial operations in the entire United States. Propellants, explosives and pyrotechnics are manufactured, loaded and assembled into complete rounds at some 29 Government Owned Government Operated (GOGO) and Government Owned Contractor Operated (GOCO) plants scattered throughout the country (Figure 1). Picatinny Arsenal in Dover, New Jersey, has the responsibility for coordinating the three commodity center pollution abatement programs for MUCOM. This results in a unified pollution abatement approach for munitions, whether they are the responsibility of Picatinny, Frankford or Edgewood.

Due to the unique nature and large volume of the items produced, the pollutants generated are also either unique or are in extremely large quantities. The areas covered in this paper concern wastes from explosives and propellant manufacture. Some examples of air, water and solid waste pollutants will be discussed along with current techniques being explored to reduce or eliminate the waste streams.

NO_x

One pollutant with which most people are familiar is NO_x. Although this gaseous emission is not unique, the quantity encountered in Army operations is extremely large, and some of the waste streams contain organic components which pose special handling problems. TNT manufacturing operations, for instance, produce 13,000 pounds per day of NO_x for 4 plants, or about 3,000 pounds per day per plant. In addition, these NO_x fumes contain such contaminants as mononitrotoluene and tetranitromethane. Sources of NO_x pollutants common to most of the manufacturing operations include nitrocellulose and TNT operations and acid production. Two sources which fall under acid production, ammonia oxidation plants and nitric acid concentrators, are the same type of operations found in private industry but are required here to support the manufacture of explosives and propellants.

Four systems have been examined as potential NO_x abatement techniques. Catalytic combustion and direct flame reduction (fume incineration) have been extensively explored by industry and will not be discussed here, except to indicate that high oxygen content and organic components in some of the waste streams make the catalytic technique ineffective. Also, fume incinerators are expensive to operate due to demands for fuel, and add to

the energy crisis. Two techniques under study for Army use are molecular sieve adsorption and scrubbing.

The molecular sieve system is being applied to a nitric acid facility at Holston Army Ammunition Plant. This NO_x stream is free from organic contaminants, and molecular sieves offer several advantages as an abatement technique. One is lower emission levels, expected to be below 50 ppm. Another is that NO_x can be recovered as nitric acid and reused. In addition, the system is a recovery technique with low input energy. Because this approach has the capability of meeting future, more stringent standards, EPA is monitoring this operation as a demonstration model to develop the economics applicable to commercial users. Figure 2 illustrates a two-bed sieve system in which one bed adsorbs while the second bed is being regenerated. Regeneration takes place by thermally heating the bed to drive off the adsorbed NO_x.

Acid and fume recovery (AFR) NO_x cannot be removed by molecular sieves due to the mononitrotoluene and tetranitromethane present. This fuel-oxidizer combination would be adsorbed as well as NO_x and could create a potential explosion hazard. As a result scrubbing techniques, shown in Figure 3, are used to remove and recover the NO_x, as well as destroy or remove the organics present. The mononitrotoluene is removed by the acid scrubber and the tetranitromethane is converted to nitroform and removed by the sellite scrubber.

TNT

Before the nation became concerned with the environment, it was common practice to dump wastes into streams running through the plants and to let the water carry them away. This is no longer an acceptable technique for disposal and new technology is having to be developed or adapted to reduce pollutants. One such pollutant stems from TNT contact with wash down and process water. TNT is soluble in water up to 150 ppm under conditions found in a plant. Subjected to radiation from sunlight or in a basic medium, the TNT forms a red complex of high intensity which can be seen in water at concentrations of as little as 1.5 ppm. Not only is the color esthetically unpleasant, but tests indicate some species of fish can be killed at concentrations as low as 2 ppm.

Activated carbon adsorption has been found to be effective in reducing TNT concentration to less than 0.05 ppm. Two activated carbon systems are currently in operation, one at Joliet Army Ammunition Plant and one at Iowa Army Ammunition Plant. Joliet uses a series downflow technique and Iowa an expanded bed parallel upflow; the basic layout (Figure 4) is the same for both systems. The carbons used are produced from bituminous coal and were selected after extensive testing. Efforts are currently being undertaken to determine the best means to regenerate the spent carbon and make it cost effective as an abatement technique.

NITRATES

Another water pollutant of concern to the Army is nitrates. Although not military-unique, quantities found in spent acid streams, spills, leaks and wash downs are much larger than those released by comparable civilian industries. Nitrates in concentrations as high as 2,000 ppm are not uncommon. Three techniques show potential in dealing with this waste.

Ion exchange has been proven feasible by commercial manufacturers. It has one major drawback for the Army in that large quantities of inorganic compounds are produced upon regeneration of the exchange system. Quantities at some plants could be as large as 50,000 pounds per day. A major potential use of these by-products is as a fertilizer. Since the Army is not in competition with private industry and since fertilizer sales is a seasonal industry, a by-product which must be sold is undesirable.

Reverse osmosis is a technique in which, if the acid waste can be concentrated to about 15%, recovery would be feasible for reuse in the plant. Unfortunately, the present membranes are not acid resistant, but newer membranes are appearing on the market which may overcome this problem. Contrary to most literature, high nitrate rejection membranes can be made and have proven feasible.

The process which appears to have the most promise for abatement of nitrates from these inorganic sources is biodenitrification. The by-products are nitrogen and a land-fillable sludge. Work is underway to pilot a system which can handle the high nitrate concentrations in a reasonable time. Initial work at Sunflower Army Ammunition Plant showed that it was feasible to decrease nitrate concentration by biodenitrification. The process was dependent on sludge concentration and temperature, and was independent of pH (5-9). Removal efficiencies of up to 90% were achieved, but detention times were too long in the early units. Current efforts are being conducted at Radford Army Ammunition Plant to improve the design and operating conditions. The pilot unit is shown in Figure 5. Primary emphasis is being placed on reducing the detention time with no loss in efficiency.

Another biodenitrification system is the biological filter concept, illustrated in Figure 6, which is being tested at Badger Army Ammunition Plant. The system concept is similar to a trickling filter in that growths on the filter media denitrify the nitrates on a continuous basis. Detention times are said to be short, and the unit is capable of handling high nitrate concentrations.

SOLID WASTES

Solid waste amounts to tons per day in Army manufacturing. The major problems arise concerning what to do about propellants and explosives.

These wastes result from settling of solids in process and wash waters, as well as from rejects and trimmings. Past techniques for disposal have been to either discharge them into the water or to open burn the solids. New processes are being developed to incinerate the solid energetics in inclosed combustion systems. Future long range systems are under study to biodegrade the energetics to reduce the energy required to destroy the materials, as well as return them to nature.

Open burning is certainly not the most desirable technique for disposing of propellants and explosives since it results in both air and water pollution. It is also uncontrolled and quite inefficient. Picatinny Arsenal has embarked on a pilot plant study program to develop controlled incineration systems for explosives and propellants. Three different types of incinerators have been explored.

Radford Army Ammunition Plant, under Picatinny's guidance, has piloted a rotary kiln incinerator system (Figure 7). Aqueous slurries of explosives and propellants in concentrations of 25% have been burned. Picatinny Arsenal has also burned slurry explosives up to 20% solids by weight in a vertical induced draft incinerator, depicted in Figure 8. This incinerator was designed in 1957 to burn liquid wastes from explosives manufacture, but has required extensive testing and some modification to allow the burning of slurries. The most advanced approach for explosives incineration utilizes a fluidized bed (Figure 9). Several advantages are evident in this system. The bed maintains a uniform temperature throughout, the unit may quickly be quenched, large energy releases are quickly dissipated and, with proper selection of bed material, no additional abatement equipment appears to be required for meeting existing or near future standards. The lab program includes tests on a catalyst bed which drastically reduces NO_x emissions. Tests will be performed with all types of explosives and propellants at various concentrations. After the lab scale work, a full scale pilot plant will be developed at Picatinny by converting the vertical induced draft incinerator to a fluidized bed design (Figure 10). Complete conversion should be accomplished by the end of 1973.

For the future, alternates to incineration are being considered. One option is biodegradation. At first thought, this procedure may not appear to have much validity since explosives have been known to be buried for years, and still function when uncovered. However, recent data has shown that, given proper nutrients and other conditions, even recalcitrant molecules such as TNT can be broken down biologically. This subject needs more investigation, but biological systems require low energy and generate end products which are readily assimilated by nature. Figure 11 presents several options available when considering biodegradation processes. One technique for biological degradation is a modification (Figure 12) of the waste digestion system used by Altoona, Pennsylvania, to degrade the garbage from the entire city. The technique appears to offer promise for disposing of not only explosive wastes, but other plant wastes as well.

Presented here is only a fraction of the projects being conducted by Picatinny Arsenal in coordinating the pollution abatement program for munitions manufacturing wastes. In all projects one feature should be kept in mind: the key word is recycle. Unless you recycle in the same or another process, abatement is like a wheel in which you simply convert pollution from one form to another, i.e., transferring pollutants from air to water, from water to solid wastes, and from solids back into the air. Without a systems viewpoint, you can become involved in a treadmill abatement scheme with little or no accomplishment. Picatinny Arsenal recognized this problem early in the program and, therefore, established investigations which stressed the minimization of pollution transferral in all projects undertaken.

Picatinny Arsenal has become a recognized leader in the industrial pollution field and has the responsibility of coordinating the entire MUCOM pollution abatement program. This entails coordination of effort between private industry as well as our sister commodity centers, culminating in a program to solve pollution problems arising from explosives and propellant production.

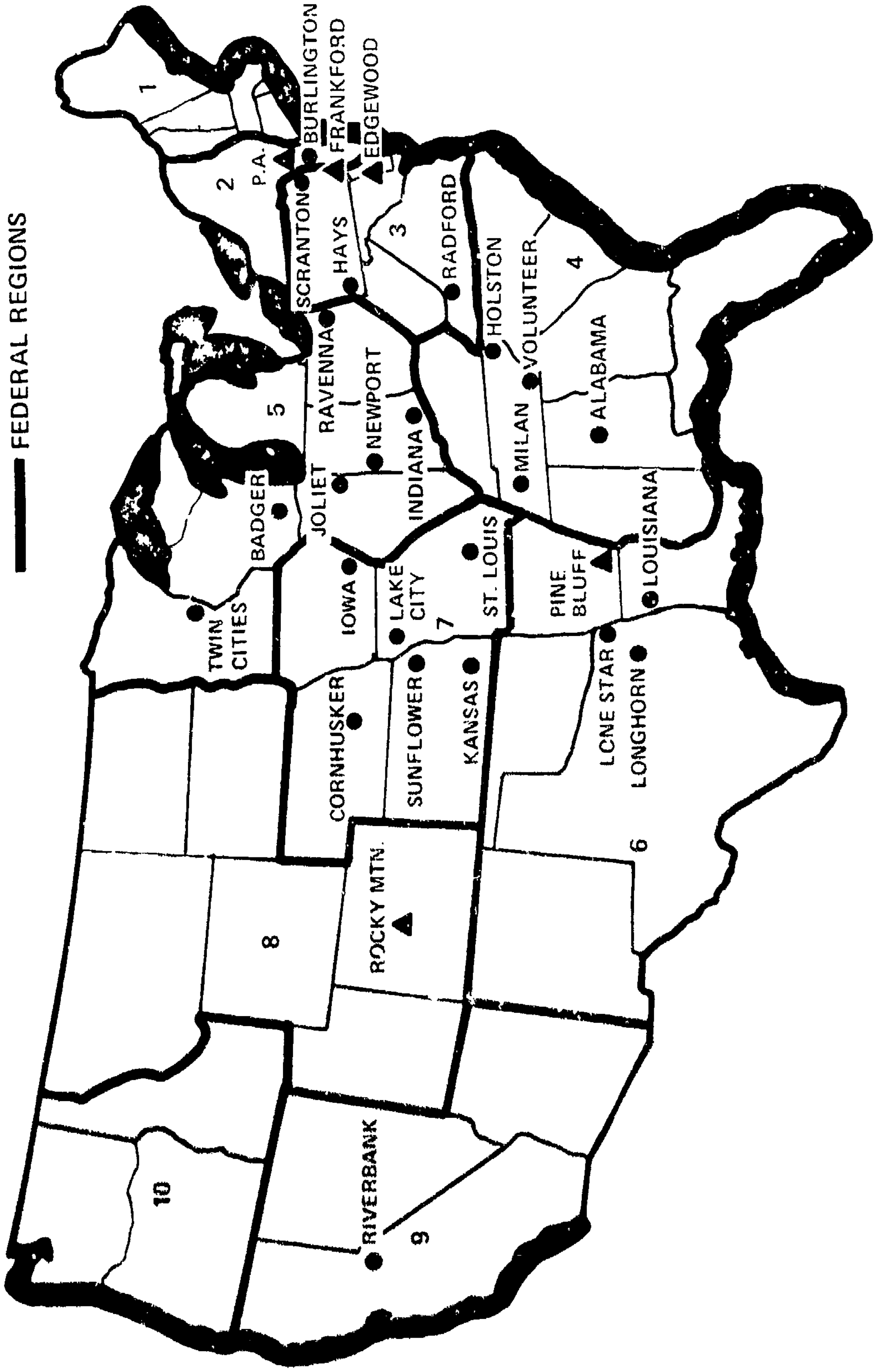

FIG. 1 MUCOM ARSENALS AND GOCO MUNITIONS PLANTS

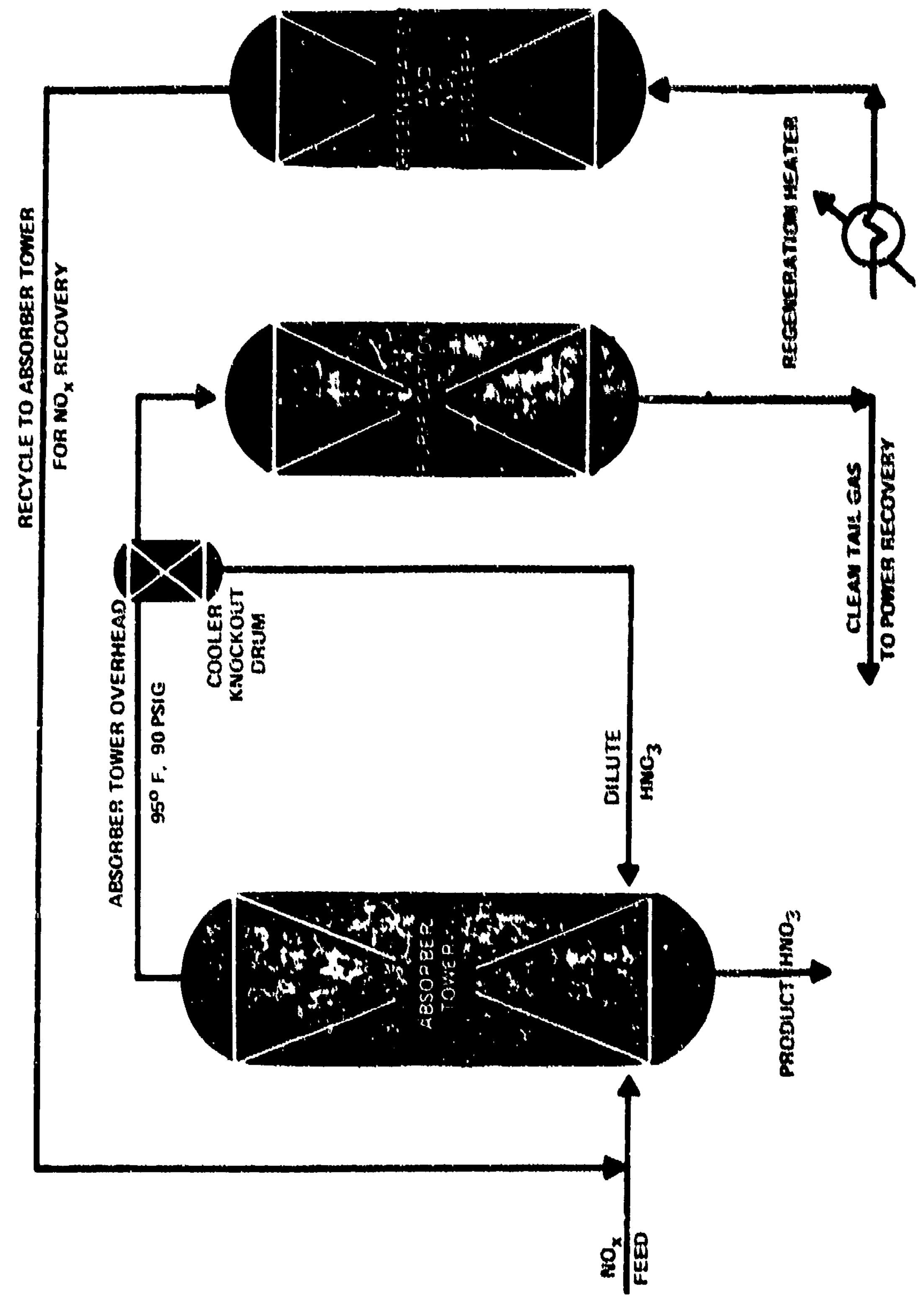

FIG. 2 MOLECULAR SIEVE ADSORPTION FOR NITRIC ACID PLANT

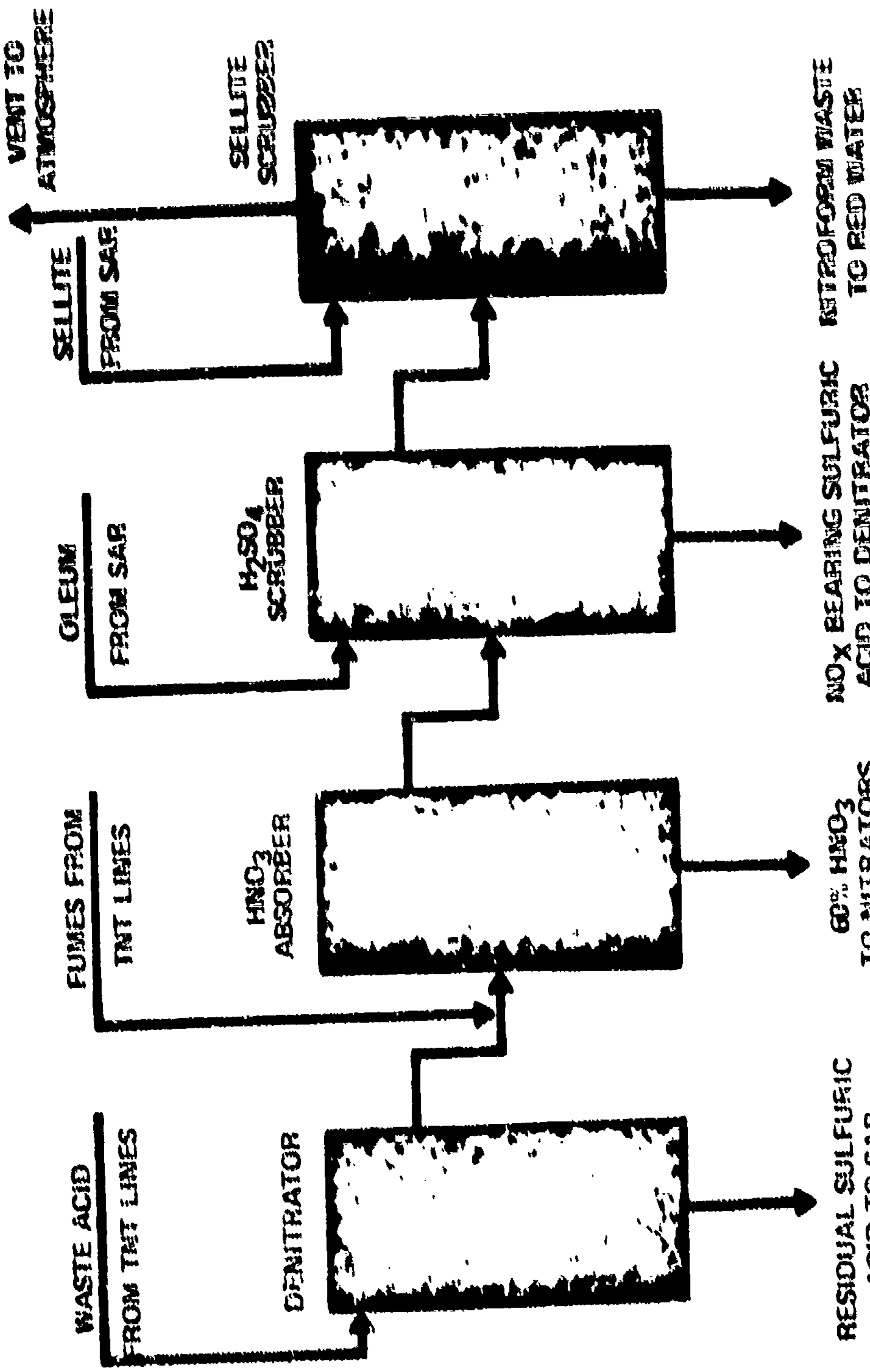

FIG. 3 AFR WITH H_2SO_4 AND SELLITE SCRUBBING

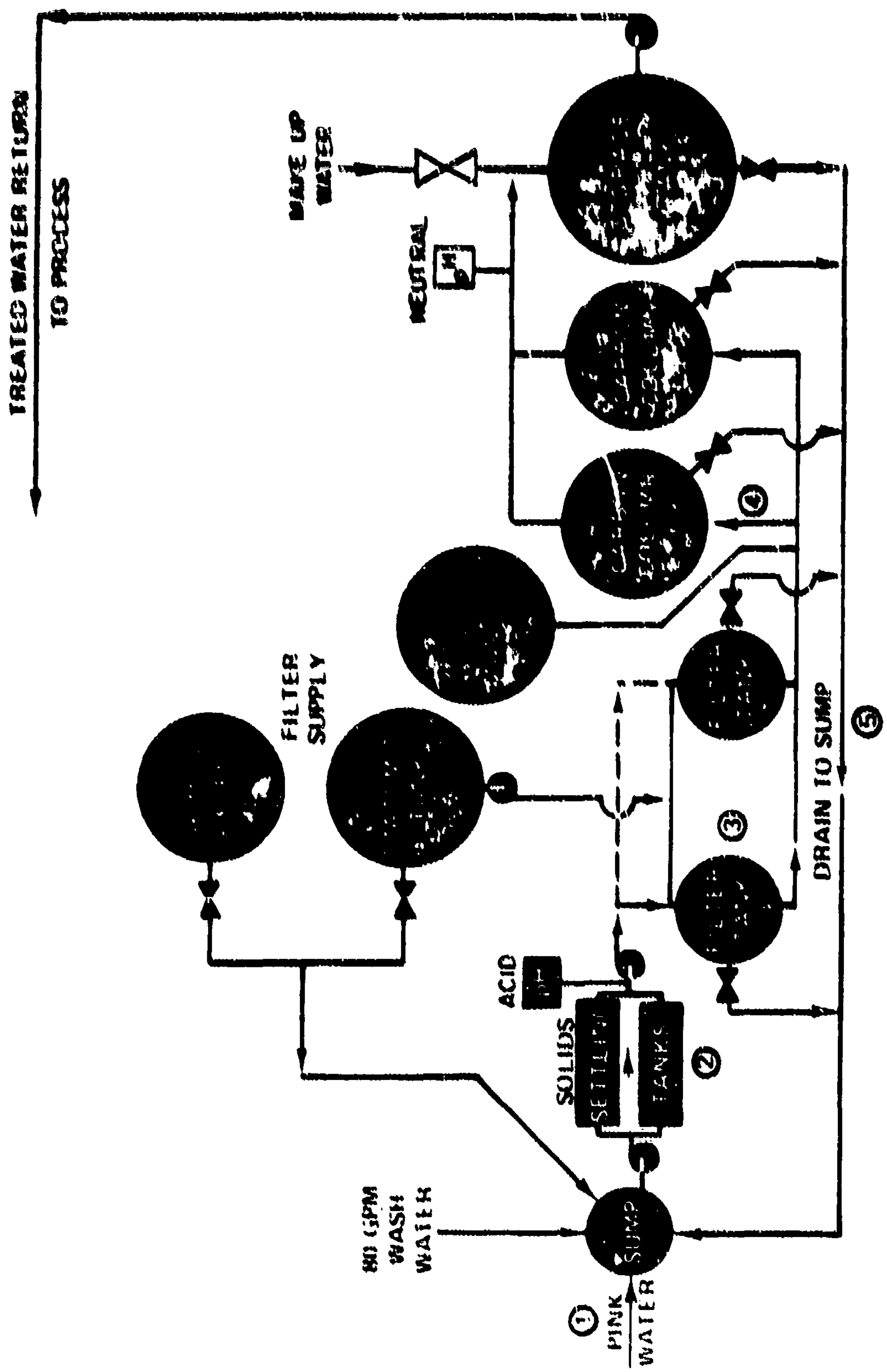

FIG. 4 PINK WATER TREATMENT FOR LAP OPERATIONS

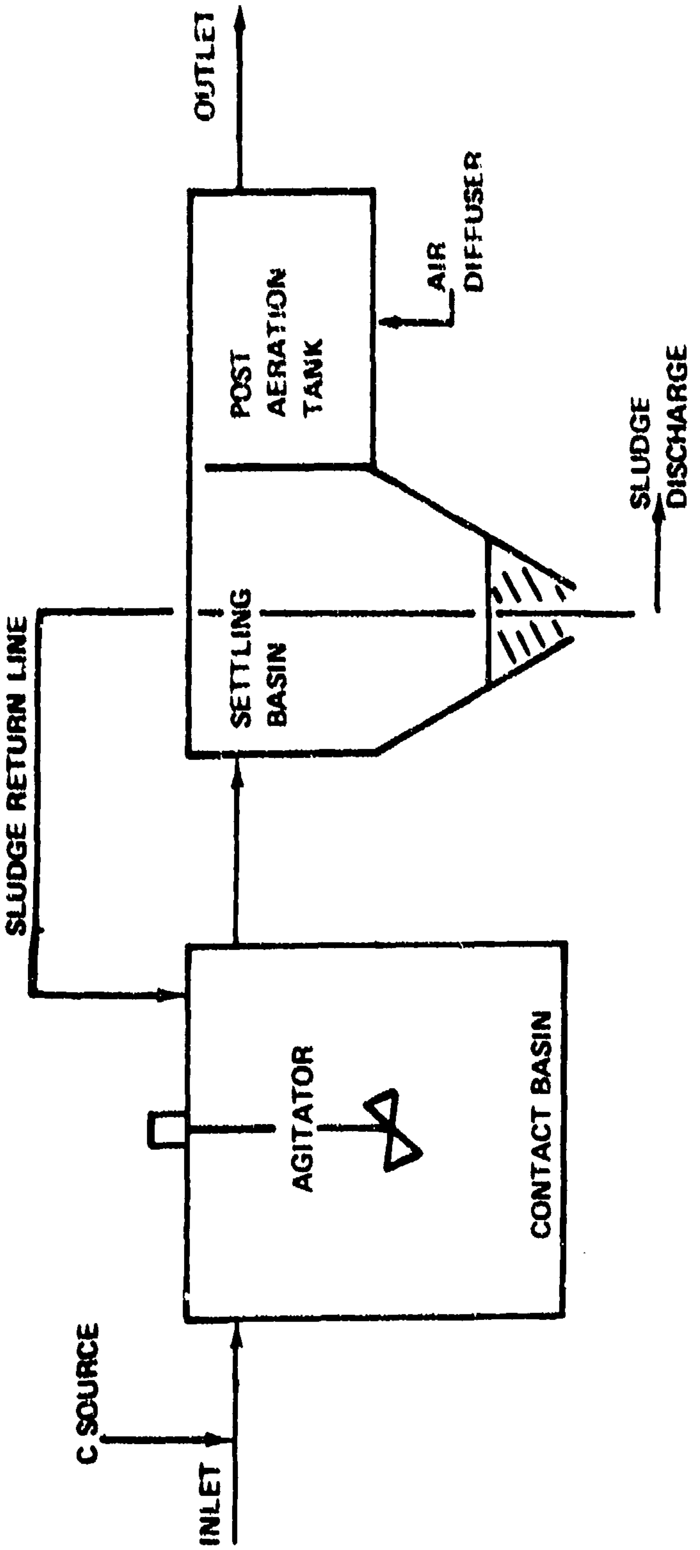

FIG. 5 BIODENITRIFICATION PILOT PLANT

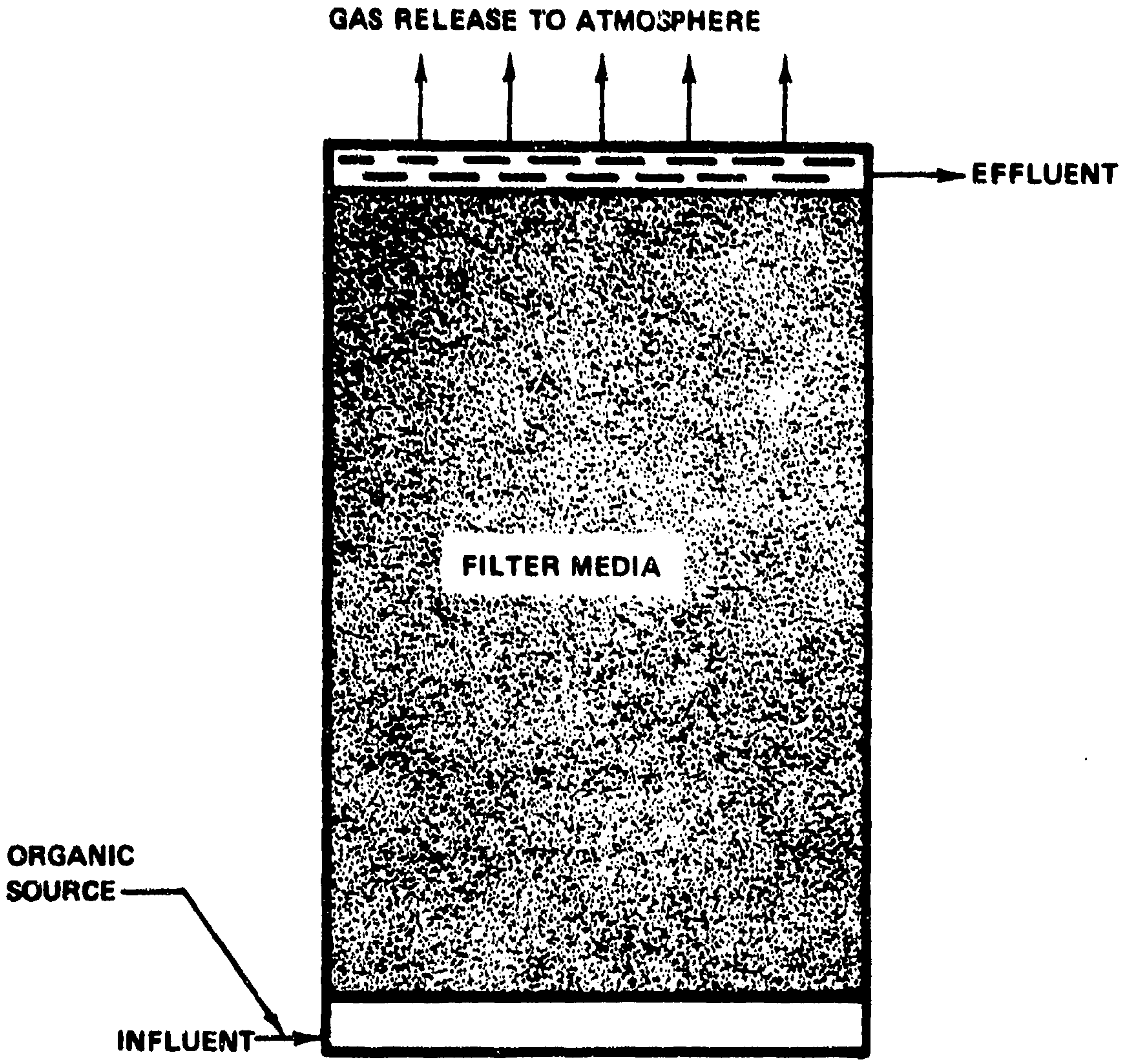

FIG. 6 DENITRIFICATION FILTER SCHEMATIC

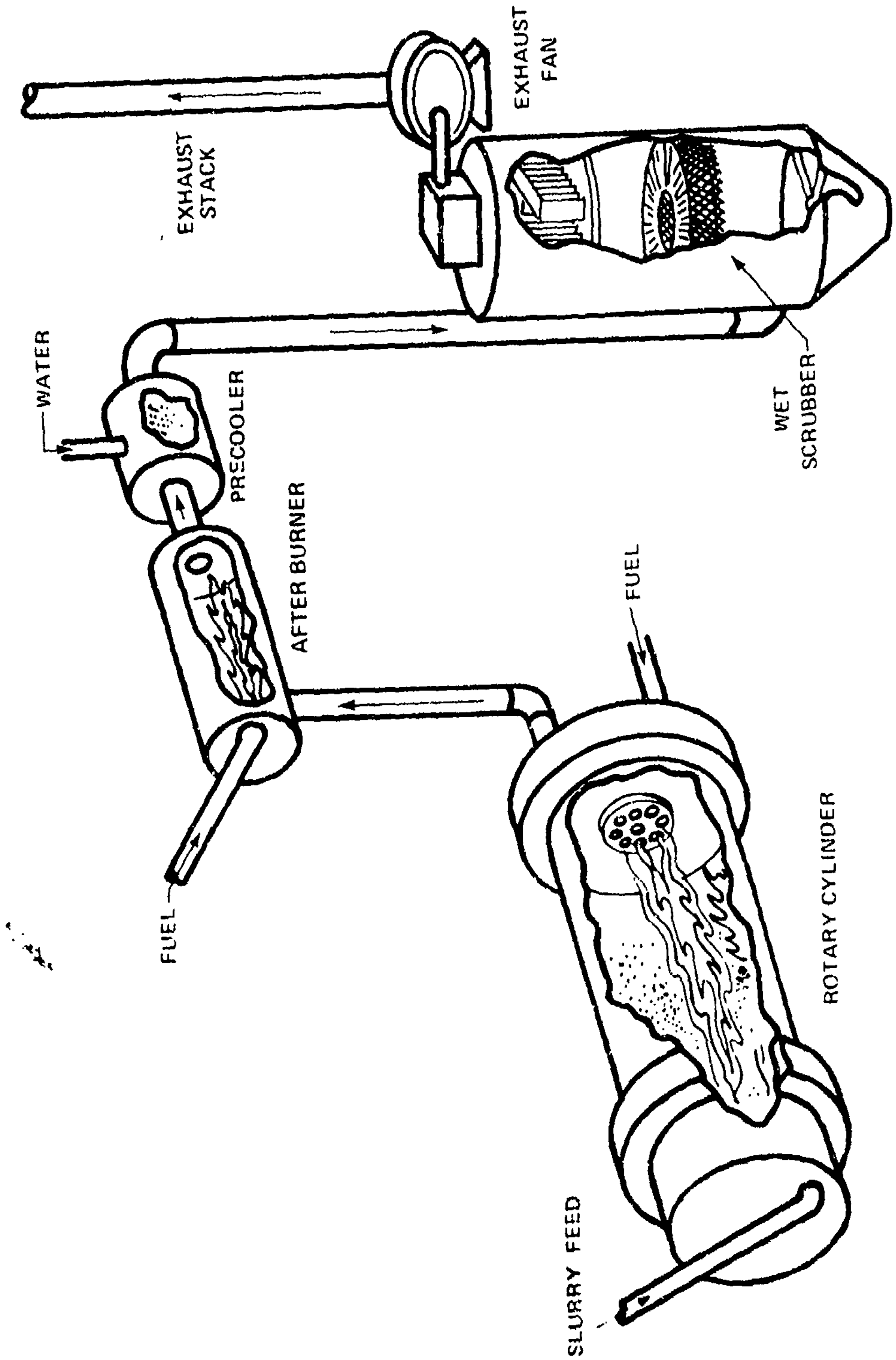

FIG. 7 ROTARY KILN INCINERATOR SYSTEM

1 OIL BURNER EQUIPMENT
2 EXPLOSIVE WASTE SLURRY LINE
3 INDUCED DRAFT FAN
4 FLUE TO STACK
5 EXPLOSIVE BLOW OUT DOOR
6 HOPPER
7 CYCLONE DUST COLLECTOR

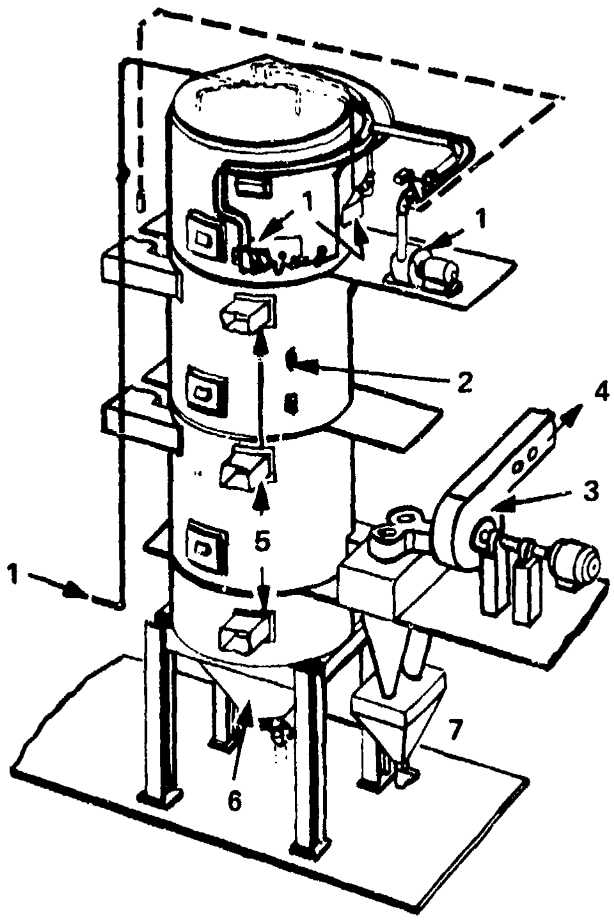

FIG. 8 PICATINNY ARSENAL INCINERATOR FOR EXPLOSIVE AND PROPELLANT WASTES

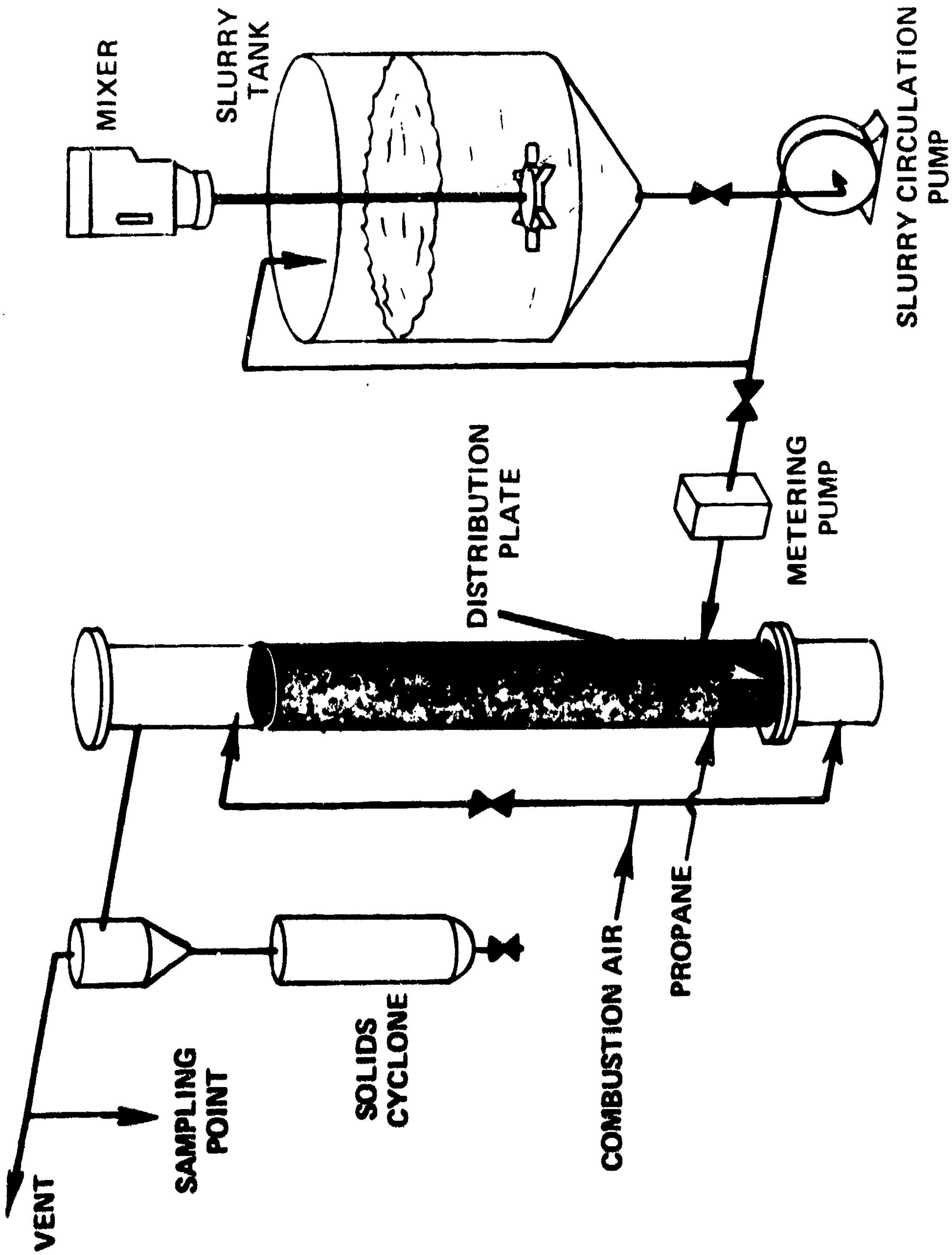

FIG. 9 LAB SCALE FLUIDIZED BED COMBUSTOR

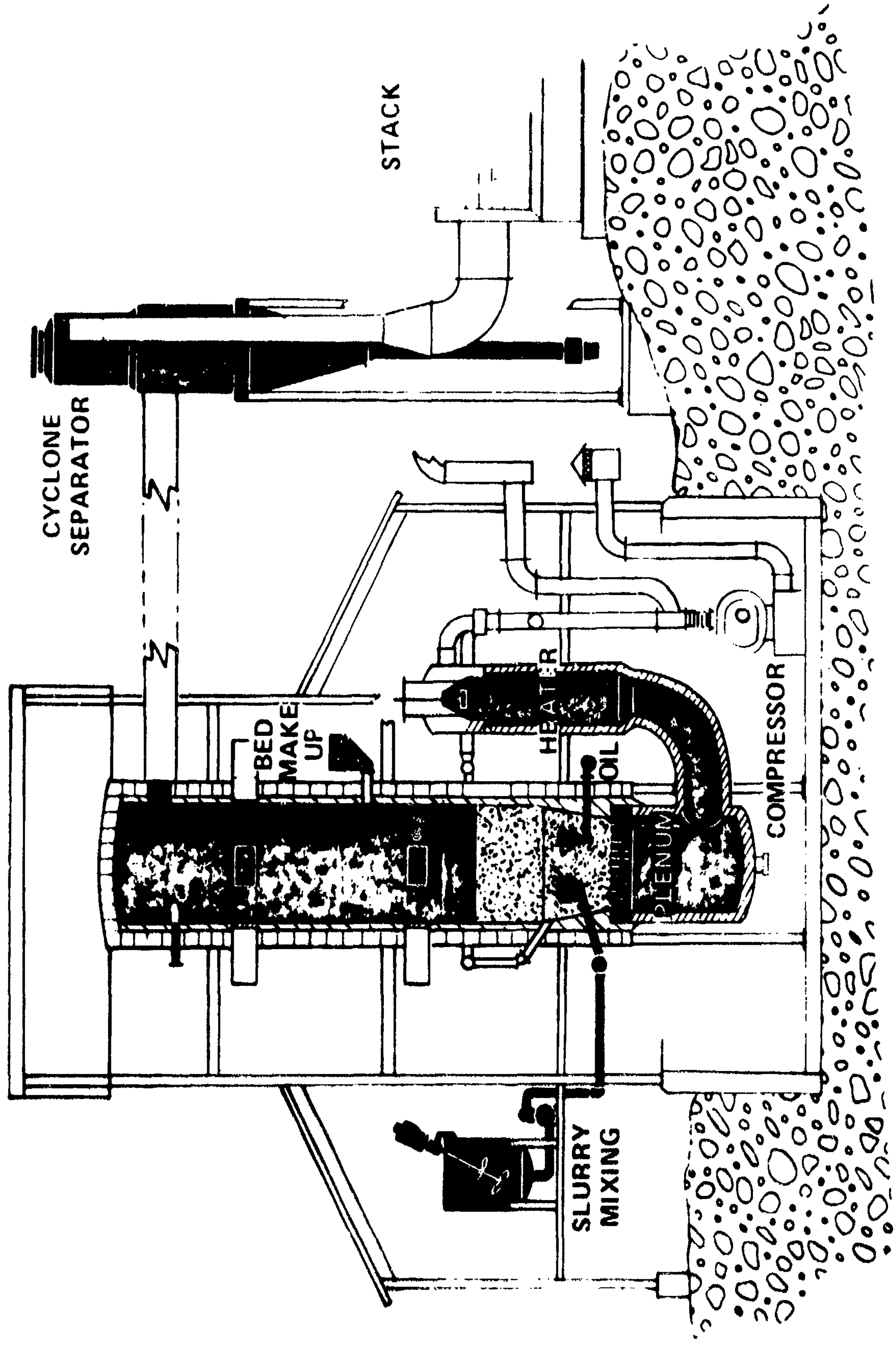

FIG. 10 FLUIDIZED BED CONVERSION P A INCINERATOR

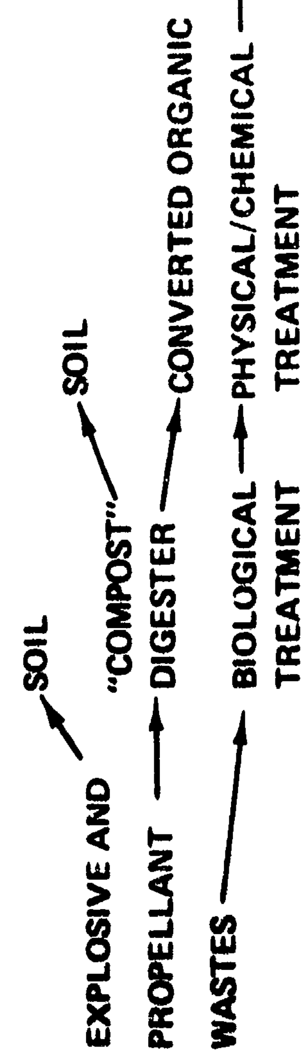

FIG. 11 BIODEGRADATION OPTIONS

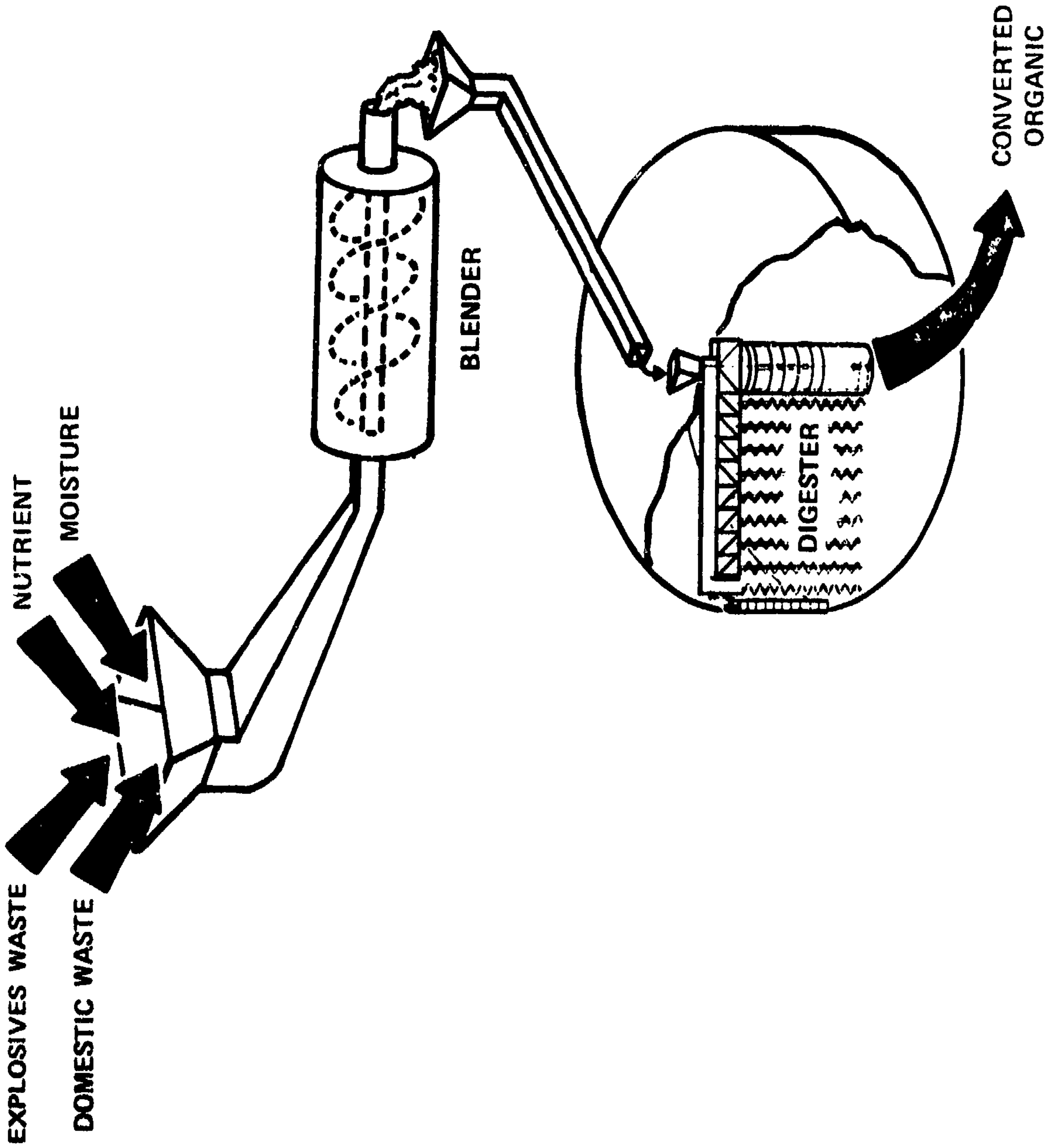

FIG. 12 WASTE DIGESTION

ENVIRONMENTAL EFFECTS OF PAST DEEP WATER DUMPS

CDR B. E. Stultz, CEC, U.S. Navy
Office of the Oceanographer of the Navy

Introduction

For years the Navy has disposed of a significant amount of unserviceable, obsolete conventional ammunition. This has been accomplished through a number of means which have included demilitarization, controlled burning, exploding, and the extensive use of deep water dumping.

Until 1964 munitions were disposed of at sea primarily by dumping over the side. Then Operation CHASE (Cut Holes And Sink 'Em) commenced. Under this program, surplus World War II Liberty ships obtained from the Maritime Administration were stripped of debris, their tanks flushed, and the hulks adapted for rapid scuttling. The ships were then loaded, towed to a designated dump site and scuttled. The average cargo ran in the order of 5,000 tons of ordnance. Nineteen such deep water disposal operations took place between 1964 and 1970, eleven of which were in the Atlantic and eight in the Pacific. During these operations some ships were loaded with chemical ordnance only and others contained conventional munitions only, fifteen to be exact. In these fifteen conventional operations, thirteen hulks detonated, nine spontaneously and four intentionally.

In the Fall of 1970 the Council on Environmental Quality recommended termination of dumping at sea, and on 7 October 1970, President Nixon stated that he would recommend legislation to stop unregulated use of the sea as a dumping ground. Immediately the Secretary of the Navy placed a moratorium on deep water dump (DWD) operations, which was followed by a Secretary of Defense freeze in April 1971 on ocean dumping of all military munitions by the United States pending the full investigation of all alternative methods of disposal.

The Chief of Naval Operations then directed the Oceanographer of the Navy to institute an investigative program to:

1. Prepare a comprehensive environmental condition report for representative past explosive ordnance DWD sites.

2. Develop criteria for selection of future sites in the event that DWD is resumed.

3. Determine what monitoring efforts would be required at DWD sites in the future.

This report pertains to conventional explosives only. Chemical munitions disposal is being handled by a separate Navy survey program, and publication is anticipated in mid-Summer 1973.

Planning the DWD Environmental Program

In designing our survey program we considered questions foremost in the public mind. The public often views ordnance related operations with an eye to catastrophic possibilities and generally views ocean dumping unfavorably. There has been alarm over possible mass fish kills and the creation of major dead areas on the sea floor. It has been feared that dumping would degrade the ability of the environment to support life or to support the normal marine food chain. This apprehension dictated that a program be developed to determine the effects of this practice.

Several Navy operational and staff commands, three Navy laboratories, scientists under contract from three major universities and representatives of the National Academies of Sciences and Engineering participated in the selection of representative past DWD sites and in the development of a sampling plan. Senior credentialed researchers from the fields of chemistry, biology, physics and geology participated as principal investigators during data collection, analysis and reporting phases.

Since it was not feasible to examine all fifteen DWD sites, two sites were selected, one representative of detonated hulks and one representative of undetonated hulks. These were: Area G off Capt Flattery in the Pacific where five ships were sunk and exploded in 8,400 feet of water and Area E, 175 miles southeast of Charleston, South Carolina where one ship was sunk in 6,300 feet of water and did not explode.

In order to be successful in this program the precise location of the hulks must be known, no small task in a mile and a half of water. We developed a two phase program -- a search phase to locate the hulk and then a follow-on environmental survey at each site. Our search phase was designed with a navigational satellite system as our survey control which provided a navigational accuracy to within one-tenth of a mile. Unfortunately, the vessels were scuttled at sites located by Loran A navigational fixes, and this system has a standard error of one to three miles. The assignment was not easy.

West Coast Representative DWD Site Evaluation (Cargos Detonated)

The search operations in Area G were conducted by Scripps Institution of Oceanography in July 1971 from the USNS DE STEIGUER, and debris from all five hulks was located. The five debris patches were defined with side-looking sonar and were shown to be nearly circular in shape and ordinarily with a diameter of 550 yards. The hulks and cargos had been reduced to rubble by the detonations, and no cratering of the sea floor was detected. Many types of bottom organisms were observed within and outside the debris fields.

In September 1971 the Naval Oceanographic Office coordinated the follow-on environmental phase of the survey. Data were collected for sediment properties, water mass characteristics, bottom biological populations and levels of possible heavy metals and explosive residues. These samples were compared to similar samples collected at reference stations outside the dump areas and comparisons were made. In addition, current meter arrays and radon measurements were made to evaluate the horizontal and vertical circulation dynamics in the area.

Sediments

The sediments at DWD Area G were collected with a bottom grab and were analyzed. No anomalies were detected in organic carbon and organic nitrogen levels, which would have indicated a significant contribution due to explosive residue. All mineralogical and physical properties were within ranges previously reported in scientific literature, which had been searched prior to the field phases of the survey.

Water Mass Characteristics

Water mass characteristics were also within the envelopes of values found in the literature. Nutrient levels observed were within the historical range of concentrations.

Circulation Dynamics

The water mass in Area G is vertically stable below the surface mixed layer with a strong boundary layer at 60 - 80 meters above the bottom. Bottom currents were measured with a bottom current meter array, and the currents encountered were considered sufficient to insure dispersion of any soluble products generated by the debris fields. Therefore, had there been any contamination resulting from residues in the area, these contaminants would essentially be confined to the bottom 80 meters of the water column and would not interact with the surface food chain in that area.

Levels of Contamination

Sediment and benthic fauna, and near bottom water samples in Area G were analyzed at the Naval Ordnance Laboratory for major munitions products. The limits of analytical detection for TNT, RDX, and Tetryl were a few parts per trillion for sea water, and several parts per million for sediment and faunal samples. For ammonium perchlorate, a limit of detection of 0.1 part per million was determined for water, sediment and faunal samples. Analysis of samples taken showed no evidence of contamination within these limits.

Heavy metals, items of great concern, were investigated, and analyses for lead and mercury were conducted by the Naval Undersea Center and the Naval Oceanographic Office laboratories. Levels observed were in the parts per million to parts per billion range. These results indicate that there is no generalized contamination by mercury in the dump area; however, the level of lead in one sediment sample was 70 parts per million, nearly an order of magnitude higher than 10 parts per million at the other nearby reference stations. But corresponding increases in lead values were not observed in faunal tissue or near bottom water samples, and although this high level was incorporated into the data, this one sample is believed to be anomalous.

Biological Investigations

The bottom living fauna was investigated by using photography, cores, grabs and trawls. Biologists from Oregon State University found the fauna to be essentially the same in quality and quantity to that sampled at the outlying reference stations. The bottom fish and bacterial populations appeared normal at the time of sampling. It should be realized, however, that sufficient time had elapsed between the final DWD operation in September 1970 and the environmental survey a year later to allow for repopulation or reinvasion of the area had any reduction in the biota occurred. The most important result is that there appears to have been no significant, irreversible damage to the bottom organisms due to the past DWD operations in Area G.

East Coast Representative DWD Site (Cargo Undetonated)

The second site surveyed -- off the East Coast near Charleston -- is the representative site for undetonated cargos. In November - December 1971 a combined search operation and environmental survey was conducted from the USNS MIZAR by the Naval Research Laboratory. This disposal operation had taken place in 1967. Upon precise location of the hulk, an environmental survey similar to that conducted off the West Coast was to be executed. The primary search area was covered by a deep towed instrument equipped with side-looking sonar, magnetometer and cameras until a search effectiveness probability of 99% was attained. Although several contacts were detected, no photographic evidence of the intact hulk of the MONAHAN, the ship scuttled, was obtained. But search photography located scattered ordnance and ordnance-related debris on the sea floor. The area had, in addition to DWD, been used as an over-the-side disposal site prior to the scuttling of the MONAHAN.

A bottom biological trawl run made during the survey passed among the largest magnetic anomalies and several acoustic contacts. When retrieved, this trawl contained rusted metal fragments encrusted with barnacles. The metal was later identified as mild carbon steel similar to that used in the hull plating of the MONAHAN, and the barnacles were identified as obligate

shallow water forms common to the Wilmington, North Carolina area where the MONAHAN had been mothballed. This circumstantial evidence indicated that the hulk is located on or very close to the track of the biological trawl. In addition, there is unexploded ordnance resting on the sea floor in the area. Although the hulk was not photographically located, it is considered a valid assumption that the area is representative of a dump site for unexploded munitions. Biological, sedimentary and water mass investigations were then conducted in this area in a manner similar to that on the West Coast.

Sediments

All mineralogical and physical parameters measured in the sediments appear within ranges previously reported in the scientific literature.

Water Mass Characteristics

Water mass characteristics are within the envelopes reported in the literature, and no anomalies in near bottom oxygen or nutrient levels were detected. The water mass in the area is vertically stable, and this vertical stability prevents exchange of surface and bottom waters and again isolates the benthic community.

Levels of Contamination

As in the West Coast Survey, there was no evidence of contamination of the sediment, benthic fauna or near bottom water by munitions products or heavy metals.

Biological Investigations

Biological investigations were conducted by biologists from Florida State University using photoanalysis of search bottom photographs. The distribution of all observable fauna was plotted and clustered into photoanalysis circles. A comparison of these areas indicated that fauna inside the dump area is virtually identical to that outside the charted dump area.

High species diversity index values obtained from grab samples indicated that many species exist throughout the area, suggesting a stable, unstressed environment both inside and beyond the charted dump area. The fauna observed and collected are restricted to the deep ocean and do not occur in shallower faunal zones, and chances are remote that benthic fauna from Area E would be incorporated into the food chain of marine organisms commercially harvested.

Summary

While it is recognized that all questions about the environmental effects of past DWD operations could not be answered by this recent investigation, the results of the parameters investigated indicate that other than sea floor litter, the deep water disposal method does not produce significant irreversible long term damage to the deep ocean environment.

The effect of cargo detonation on fish would probably be the most serious result of DWD. However, it is transient, and the mobile fish community will return to the blast area. This transient effect would be minimized if dumping activities were conducted in areas and seasons in which fish concentrations were minimal. There were no indications of blast effects at the bottom or to bottom living organisms. Analysis for heavy metals and explosive product residues indicate that there is no generalized contamination by lead or mercury at the dumping sites. Considering munition products, no notable concentrations of TNT, RDX, tetryl or ammonium perchlorate were detected in the near bottom waters, sediment or biota samples at any of the sampling sites.

As a result of the environmental inspections at these selected representative DWD sites, the Department of the Navy's report, entitled Environmental Condition Report for Numbered Deep Water Munitions Dump Sites presents a dump site selection profile which is a list of twenty standard characteristics of a proposed area. Although there are efforts to develop alternate disposal methods, if the need to resume deep ocean dumping of conventional munitions should arise, this characteristics list, the selection profile, could be employed as an aid in minimizing stress to the marine environment.

In respect to future monitoring at past DWD sites:

1. A survey of the five remaining conventional DWD sites would require a large commitment of resources.

2. The return of such an investigation in terms of additional scientific understanding of past DWD operations would be small.

3. Should additional investigations of DWD sites be conducted in the future, the greatest return would be realized by resurvey of the West Coast site in five years, where baseline data now exists.

Based on this comprehensive environmental survey by scientifically creditable personalities and institutions, deep water dumping of conventional munitions produces no significant long-term, irreversible effects on the marine environment.

SHOULD WE DUMP OR DETONATE?

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The question of dumping vs detonation treated in this paper refers to a method of bulk munitions disposal known as a "deep water dump (DWD)," or "deep water disposal." In such an operation an old ship hull is loaded with obsolete and deteriorating munitions junk, is towed out to sea to an authorized disposal area, and is sunk--hull and cargo together.

At the present time this method of munitions disposal is not authorized by the Navy. And it may be that this method will not ever be used again. If the decision is made at some future date, however, that a deep water disposal is the least undesirable alternative, then many factors that I will not even mention in this talk will be weighed in arriving at that decision.

This paper does not recommend for or against deep water disposals of munitions. Rather, it considers the mechanics of the operation if such a disposal is planned. Several staff studies of this sort have been made at NOL on our pollution-abatement task sponsored by the Naval Ordnance Systems Command. The studies I will draw from most heavily today are recent NOL reports by Sherman and Price[1], and one by Young[2].

The question we are asking here is: Should we dump or deliberately detonate a deep water disposal ship loaded with old high explosives munitions? Note that we are not including any chemical or biological agents, or any radioactive materials in the load to be dumped. We are talking strictly about old munitions loaded with high explosives.

Two of the most important questions that must be weighed in judging whether the disposal ship should be quietly sunk, or purposely detonated are: (1) the environmental effects, and (2) the safety of the alternative choices. I will use the symbols plus, minus, and zero to indicate the relative ill effects of a dump and a detonation. A plus does not signify a desirable improvement, of course, but merely that it is less undesirable than a minus.

The environmental question can be separated into long-term and short-term effects. As we have just heard in the preceding paper[3], surveys of past disposal sites indicate that there were no significant long-term, irreversible effects on the environment from either dumping or detonating the munitions load. Consequently, we can assign a "zero" on the question of long-term effects for either dumping or detonating the munitions ship.

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[1] Sherman, Peter S. and Price, Robert S., "Selection of Depth for Intentional Explosion of a Deep Water Dump," Naval Ordnance Laboratory Report NOLTR 72-115, 5 Feb 1973

[2] Young, George A., "Guide-lines for Evaluating the Environmental Effects of Underwater Explosion Tests," Naval Ordnance Laboratory NOLTR 72-211, 13 Feb 1973

[3] "Environmental Effects of Past Deep Water Dumps," by Commander B. E. Stultz, these Proceedings

As for the short-term effects on the environment, we have put a plus on the side of dumping and a minus on the side of detonating. The most significant short-term environmental effect of the operation would be the effect on biologicals. And on this score, detonation would certainly be more disruptive than dumping.

As for the second question, safety, there are again two aspects to be evaluated: one I have called "future shock," with apologies to Mr. Alvin Toffler, and the other "control."

By future shock mean just that. If a dump is made without detonating the load, we have no guarantee that there will not, at some future time, be a detonation, of some unpredictable violence. It is not an attractive prospect to plant a ship-load of detonatable munitions, even in an authorized dump location that is marked as a hazardous area on charts. We cannot really forsee all the activities that may take place on the seabed in the future. Even now, commercial fishing boats are operating at ever greater depths. And it is conceivable that the "disposal area" notice on a navigation chart will not always guarantee that a dump site is left undisturbed. Consequently, I have put a "minus" for this point on the side of a dump.

From the point of view of future shock, detonation rates a "plus," by comparison with dumping. If the load is purposely detonated, the bulk of the more sensitive materials will be destroyed. The munitions that are not destroyed will be distributed over a fairly large area; thus, if they were later activated, the explosions would probably be small and relatively innocuous.

The other factor to consider under safety is "control." One has far less control over a dump than over a deliberate detonation. In fact, judging from past disposals, chances are three to one that such a load of munitions <u>will</u> detonate, rather than sink peacefully to the bottom, even though it has not been deliberately fuzed, and there is no way of knowing at what depth detonation may occur. So on the question of control, again I have assigned a plus to deliberate detonation and a minus to a dump.

Thus, as summarized in Figure 1, from consideration of the environmental effects and the safety aspects of a deep water disposal of munitions, a deliberate detonation appears to be more desirable than a dump. The detonation has the disadvantage of a short-term environmental trauma, but it has definite advantages from the point of view of safety. In short, our recommendation is: don't dump, detonate.

We also have a further recommendation: select the detonation depth to minimize adverse environmental effects and to minimize the safety hazards that are always present in operations with explosive materials. The remaining discussion will deal with this second subject, the choice of a best depth for a deliberate detonation. I believe that today we can recommend a "best depth." This was not so a couple of years ago when the ban on deep water dumps was imposed. But studies undertaken since that time have given us more information about how to improve deep water disposal operations.

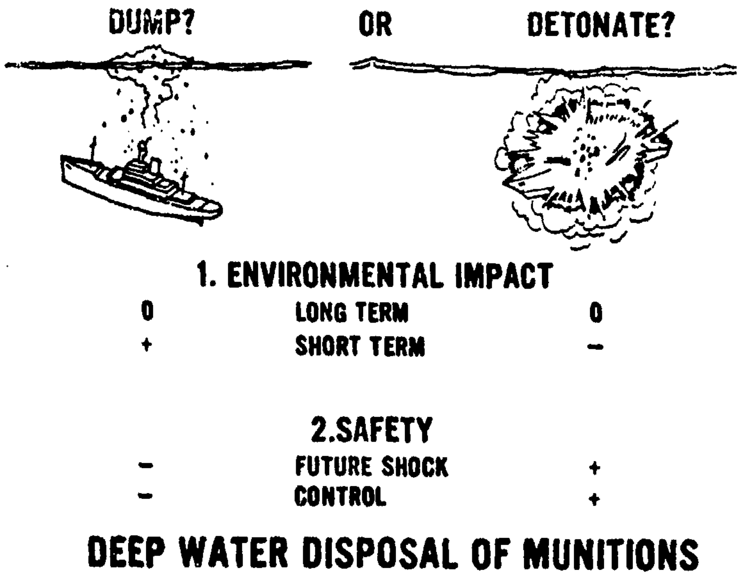

Figure 1

The two major short-term effects of a detonation that may threaten the environment are (1) the detonation products that are generated by the explosion, and (2) the shock damage to biologicals in the vicinity.

We will first consider the detonation products--what they are, and where they are distributed. These questions are treated in Young's[2] recent report.

In Table 1 the detonation products of a TNT explosion are listed here in two columns.

TABLE 1

DETONATION PRODUCTS OF TNT

Carbon Dioxide	Hydrogen
*Carbon Monoxide	Ammonia
Carbon	Methane
Nitrogen	*Hydrogen Cyanide
Water	Ethane
97% (Wt.)	3% (Wt.)

In the left-hand column we see that 97% of the explosive weight is converted to familiar, and generally innocuous, chemicals: carbon dioxide, carbon monoxide, pure carbon, nitrogen, and water. The traces of materials that make up the remaining 3% of the weight are listed in the right-hand column: hydrogen, ammonia, methane, hydrogen cyanide, and ethane. In a moment we will look at the concentrations of carbon monoxide and hydrogen cyanide--the two suspect components that are marked with asterisks.

These detonation products are distributed among three general areas, depending upon the size and depth of the explosion. Some products may escape into the air, some may be desposited in a surface pool, and some may remain in the water column directly above the charge.

The so-called "surface pool" is generally a large, very thin layer of surface water centered above the explosion. To give you an idea of typical surface pool dimensions, for a 2,000 ton explosion (a weight of charge that might be contained in a DWD), the pool will be perhaps 3-1/2 miles wide and only about 250 feet deep.

Figure 2 shows how the distribution of products from our 2 kiloton charge varies as we change the detonation depth. The percentages of solid and gaseous products deposited in the air (A), in the surface pool (B), and in the water column (C) are indicated for each of three depths. On the right-hand side of the figure, for the deepest detonation at 6000 feet, all products remain in the water column. Going to shallower detonation depths as we move from right to left, we find, not surprisingly, larger percentages of the products being deposited in the surface pool and in the air above the explosion. For the extreme case of a detonation at the surface, all of the products will initially be thrown up into the air. Some water will be entrained and mixed with the products. Some of the solid products will fall back to the surface with the water particles and float there in a thin layer. The remainder of the solids and virtually all of the gases will remain in the air.

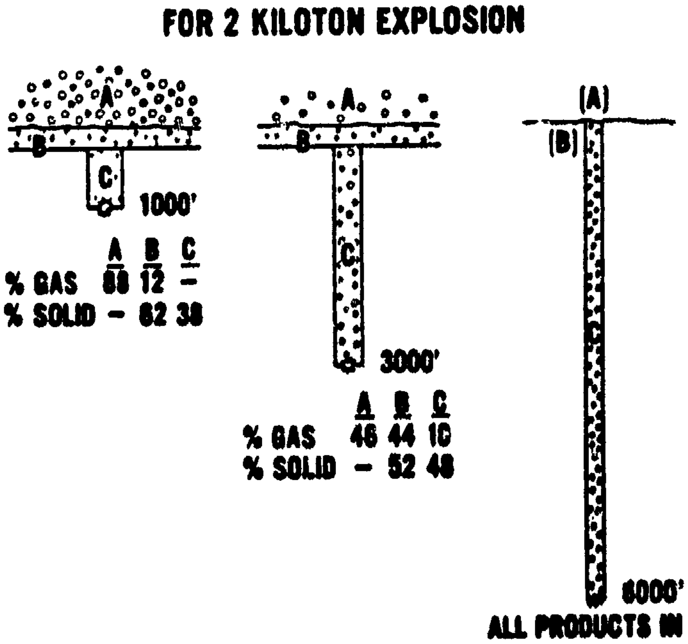

Figure 2. DISTRIBUTION OF UNDERWATER EXPLOSION PRODUCTS

For reasons that will soon become apparent, we are particularly interested in a surface detonation, so let us examine the concentrations of various gaseous products thrown out into the air. Table 2 shows the concentrations, in parts per million (ppm), of the products of a TNT charge detonated at the surface.

The first column of Table 2 shows Young's estimates of the maximum concentrations of explosion products for a TNT charge detonated at the surface. Note that these are maximum values, immediately above the charge, before any dilution has taken place. These concentrations will be lowered very rapidly by the turbulent mixing of products and air.

The second column of Table 2 shows concentrations of these same materials in the atmospheric background of "clean air" at sea level.

TABLE 2

CONCENTRATIONS OF DETONATION PRODUCTS (PPM BY VOL.)

Product	TNT Explosion at Surface (max.)	"Clean Air" at sea level	Threshold Limit
Carbon Dioxide	329	316	5000
*Carbon Monoxide	522	0.1	50
Nitrogen	348	781,000	--
Water	405	20,000	--
Hydrogen	122	0.5	--
Ammonia	42.5	0.00002	50
Methane	26.2	1.4	--
*Hydrogen Cyanide	5.30	--	10
Ethane	0.98	--	--

The last column on the right of Table 2 shows threshold limit values[4] that have been assigned by the occupational safety and health administration. These threshold limits are considered acceptable hourly exposures for personnel during an 8-hour work day. They are included here to give us some semi-quantitative feel for how seriously a surface burst might contaminate the air.

Asterisks in Table 2 indicate the two detonation products mentioned earlier as possible problems--carbon monoxide and hydrogen cyanide. The carbon monoxide concentration before dilution is about 10 times the threshold limit. Some 100 meters downwind of the explosion, however, the concentration will probably be only about 1/2 part per million. In view of the threshold limit value of 50 and the 1/10th background value, this does not appear to be a serious contamination level. Similarly, for hydrogen cyanide, by comparison with the threshold of 10, the explosion's brief concentration of 5.3 parts per million before dilution does not seem to be a serious hazard.

Granted that we cannot guarantee that no detonation of munitions would ever produce more damaging products than those shown in Table 2, it seems reasonable to conclude that, in general, the explosion shock effects will be a greater hazard to biologicals than the detonation products themselves. Let us look now at how the shock effects vary with depth of detonation.

For an underwater explosion, the biologicals we are most concerned about are fish. Specifically, they are fish that have gas-filled swimbladders, for these are the creatures most vulnerable to underwater shocks. A recent study of explosions effects on swimbladder fish[5] shows that for large explosions such as our typical 2 kiloton burst, the deeper the detonation, the larger the area within which fish will be damaged by the explosion. In fact, the best depth of detonation for minimizing fish-kill, is the surface. So perhaps we have a simple solution to our problem of protecting the water populations--detonate the ship-load of munitions without sinking it.

Admittedly, this suggestion seems to be begging the question of environmental impact. Are we not just protecting the water at the expense of the air? I don't think so. I believe that the total environmental effects are minimized by selecting the surface, rather than some depth in the water, for our detonation.

The biological populations available to be harmed by the explosion are fewer in the air than in the water. Certainly the air-borne biota are far less significant to man's "food chain" than are the water-borne biota. Rightly or not, I think most of us feel more protective towards the tuna population, say, than towards the seagull population.

Furthermore, it seems possible that if flocks of swans, or ducks, or whooping cranes were in the vicinity of the operations they might be frightened away from the danger zone by the activities on the surface. Schools of fish that happened to be in the area would have no such warning before an underwater detonation.

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[4] "Threshold Limit Values for 1971," Occupational Hazards, Aug 1971, pp 35-40

[5] Christian, Ermine A., "The Effects of Underwater Explosions on Swimbladder Fish," Naval Ordnance Laboratory Report NOLTR 73-103, 27 July 1973

Even though a surface detonation may minimize adverse environmental effects of a deep water disposal, there remains the other factor which we must also weigh--the safety question. In trying to solve any two problems simultaneously, we are all familiar with the frustration of finding that the best solution for one of the problems is the worst solution for the other. In the present case we have an exception to that rule of frustration: a surface detonation is also preferable for safety.

The report by Sherman and Price[1] points out that the safest method of detonating a munitions cargo is by remote control. A few special explosive charges, designed for detonation by a radio link, could be placed in strategic locations while the hull was being loaded at dock. After the ship had been towed to the disposal site, these slave charges could be initiated with the radio control unit on board the command ship, and they, in turn would detonate the load. This technique of remote control activation has often been used in the past for such purposes as turning on instruments at distance, and detonating large charges. Moreover, such radio links have a history of being safe, reliable, and economical in use.

With a surface detonation, several hazardous operations associated with sinking the hull could be eliminated. No one would have to go aboard the explosives ship to open valves, so there would be no need to transfer personnel from one ship to another. At-sea transfers are sometimes quite hazardous operations.

Secondly, it would not be necessary to equip the disposal ship with special valves and soft patches which would be opened to hasten sinking. Such special valves might make the ship less seaworthy if bad weather were encountered during the tow.

The final, and probably most significant, advantage of a remotely actuated surface detonation is better control of the operation than would be possible with a submerged detonation. The munitions ship would be in view at all times. Detonation could be postponed if planes or ships unwittingly entered the danger zone. The most anxious moments of past disposal operations would be removed: the waiting--perhaps for an hour or for several hours--until the drifting ship finally sank: the uncertainty of whether the load would self-detonate at a shallower depth than it was intended to fire.

In our opinion, these safety advantages probably outweigh the environmental ones noted earlier.

In summary:

(1) If a deep water disposal is undertaken, we recommend that the munitions be detonated, not dumped.

(2) And to minimize both the environmental impact and the safety hazards of the operation, we recommend DON'T DUMP - DETONATE ON THE SURFACE.

ENVIRONMENTAL CONSIDERATIONS ON EVENT MIXED COMPANY

Major William B. Shepard

Defense Nuclear Agency

INTRODUCTION

During the years 1964 to 1970 the Defense Nuclear Agency sponsored six large 500-ton high explosive tests, where TNT was used to simulate the blast and shock effects of nuclear weapons. The tests were used to verify blast hardness levels of surface military systems, below ground structures, and to verify calculational techniques and empirical predictions for equipment and structures that cannot be tested directly.

Six months ago on the 13th of November 1972, the Defense Nuclear Agency (DNA) carried out the seventh 500-ton high explosive test, Event MIXED COMPANY, at a test site near Grand Junction, Colorado. A general description of the test will be given, followed by a discussion of some of the events leading to the filing of the environmental statement for the MIXED COMPANY test.

TEST DESCRIPTION

The MIXED COMPANY 500-ton high explosive test provided an environment to simulate the air blast and ground shock effects of a nuclear weapon on military systems and critical components

so that military systems can be certified to survive required levels on the nuclear battlefield. In addition technical data related to survival of our strategic MINUTEMAN forces was obtained. MIXED COMPANY included tests of helicopters, tactical missiles, model silos, antennas, tracked vehicles, military personnel shelters, aircraft shelters, and calibration tests. In order to anticipate questions that might arise, and to provide information to the public, a draft environmental statement (prepared in accordance with Department of Defense Directive 6050.1 dated 9 August 1971, and the National Environmental Policy Act of 1969) was filed on 23 June 1972 with the Environmental Protection Agency, the President's Council on Environmental Quality, and other agencies, including Colorado government authorities. The final environmental statement was filed on 6 October 1972. A discussion of some of the events leading to the filing of the environmental statement and some conclusions follow.

EVENTS LEADING TO THE STATEMENT

In the fall of 1970 the U. S. Military Services, Defense agencies, and other government agencies were surveyed for large scale high explosive testing requirements so that a

determination could be made as whether, when, and what kind of high explosive tests should be planned. By spring of 1971 sufficient information was available to begin planning for a test in the fall of 1972. Planning included consideration of scope of experiments, location of test, environmental factors and logistic support. In March of 1971 the U. S. Army Waterways Experiment Station (WES) was requested to search for an experimental site based upon geologic, environmental, and logistic factors. In April 1971 DNA requested that experimental proposals be submitted by July 1971. In May 1971 Field Command Test Directorate was selected to conduct the test and arrange for on site logistic support. In June 1971 the technical staff was selected, and the DNA technical review board reviewed technical proposals in July 1971. In August 1971 the explosives were ordered. In September 1971 the test site near Grand Junction, Colorado was selected and notices of approved experiments were sent out. In November 1971 Canadian, British and German experimenters were invited to participate. In December 1971 detailed work on an environmental assessment was begun by Field Command Test Directorate, construction proposals were reviewed, test layouts published, and calibration tests planned. In February 1972 WES was selected to do site

construction, construction cost estimates were given to experimenters, and the Air Force decided to test aircraft shelters. In March 1972 Field Command Test Directorate completed an informal environmental assessment, with the conclusion that a statement is not required because it was expected that there will be no irreversible effects on the quality of the environment.

In preparing the environmental assessment for the MIXED COMPANY test, DNA contacted the Colorado Game, Fish and Parks Department, the US Geological Survey, the US Bureau of Land Management, and the Western Environmental Research Laboratory of the Environmental Protection Agency.

Field Command Test Directorate set up field operations and began preparations for the calibration tests of June and July 1972. In April 1972 the Governor of Colorado was advised of the test, as were local news media personnel, and local officials. In May 1972 a reporters' questions indicated that a controversy might develop and a draft environmental statement was filed in June 1972. In view of the increased interest that circulation of the draft statement might create, specific steps were taken to hold press briefings, and information was provided to the Colorado Congressional delegation.

The draft environmental statement was sent in June 1972 to the Governor's office, the Colorado Department of Local Affairs, the Colorado Department of Health, the Colorado Department of

Agriculture, the Colorado Game, Fish and Parks Department, the Mayor of Grand Junction, the Mesa County Board of Commissioners, the Denver Regional Administrator of the Environmental Protection Agency, and the Colorado Bureau of Land Management as well as Washington DC based Federal agencies.

Comments on the draft statement were received in July and August 1972 from the Department of the Interior, the Department of Agriculture, the Environmental Protection Agency, the Federal Aviation Agency, and the State of Colorado.

The draft environmental statement was then revised to include consideration of areas suggested in the comments, and a final statement was filed (together with comments and a summary of actions on comments) with the Council on Environmental Quality on 6 October 1972. Topics to which information was added are: effect on water supplies; description of flora, fauna, and climatology; and effects on recreation, archaeological and other related cultural features in the area.

The test was successfully conducted on 13 November 1972, and clean up of the site was begun following the test before winter weather halted operations. Restoration is expected to be completed in 1974.

CONCLUSIONS

A fair effort is required to determine the critical issues, make coordination with the local populace and governmental officials, develop necessary technical expertise, develop and carry out a public information plan, as well as to institute controls, take samplings, and plan for land restoration. The plan for events related to environmental considerations must be detailed and also flexible.

Another conclusion is that in view of concerns for the preservation of the environment in the context of increasing population and industry densities and the National Environmental Policy Act of 1969, the impact of the formal assessments and statements on defense projects such as nuclear weapons effects research has not fully been assessed. Common trends and common problems have been identified and the knowledge and experience gained in tests such as MIXED COMPANY can make environmental assessments for future projects less difficult to prepare.

AMMONIUM NITRATE BASED EXPLOSIVES FOR MILITARY APPLICATIONS

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ABSTRACT

Conventional high explosives, used by the military for various applications, present many environmental problems during their manufacture, loading, demilling, and disposal. This paper describes recent research and development efforts where ammonium nitrate (AN) based explosives have been used to both accomplish specific technical objectives and to reduce the environmental impact. AN based binary explosives have now been used at the Naval Ordnance Laboratory for experimental general purpose bomb fills, explosives excavation, and nuclear blast simulation applications. The impact of these explosives on the environment will be compared with that of conventional explosives.

An Investigation of the Sound Pressure Levels Produced by Explosions in Bombproofs

by

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Naval Ordnance Laboratory

Introduction

The study and development of new explosive materials is one of the primary functions of the Naval Ordnance Laboratory. Concomitant with this function is the testing of small quantities of explosive materials here on NOL grounds. A majority of these tests are conducted in explosion resistant facilities called "bombproofs". These facilities serve a dual purpose: (1) to contain the explosion in order to reduce the damage to instruments located near the test area, and (2) to reduce the noise and damage produced by the detonating explosive.

Currently, NOL operates 5 bombproofs. These are listed in Figure 1. Also shown in this figure are some of the salient features of each building. Building 324 is considered a "typical" bombproof, so its construction will be examined in more detail. Figure 2 shows the configuration of this building. The actual test chamber is 10' x 15' x 8 1/2', with three viewports for camera observation. The walls of the test chamber are protected from fragments by 1-inch armor plate backed by 1 5/8-inch wood. A four-foot wide labyrinth leading out of the test chamber prevents fragments and blast from having a direct path to the outside. The heavy steel door in the labyrinth closes a 16.6 square foot vent area and encloses a total internal volume of 2,010 cubic feet. All walls, ceilings, and flooring in the test chamber are two-foot thick reinforced concrete (Ref. (1)).

To further control the amount of noise produced by these explosive tests, NOL has devised a "Noise Control System", outlined in Figure 3. Any firing of 1/2 pound or more of explosive in an unsealed bombproof must go through this system. Before a firing is approved, both the wind speed/direction and temperature are checked. For firing approval to be given the wind must be less than 5 mph from the N.E.-N.W. quadrant or less than 15 mph from the remaining directions. The lapse rate must be at least 2°F/100 ft. A temperature inversion, the opposite of a lapse, can result in the focusing and enhancement of the noise at locations outside NOL.

In spite of these precautions, complaints of excessive noise and vibration caused by our bombproof tests have been and still are being received from some of the neighboring private homes. Figure 4 is map of NOL and its surroundings. The explosive test area is indicated as well as the location of many of the complaints.

Because of these continuing complaints, NOL has initiated a program to determine the exact sources of these problems, and then to find ways to eliminate them.

In 1966, NOL, in conjunction with the U.S. Bureau of Mines, made a series of measurements at a private residence which is located some 3000 feet from the "noise source", Building 314. The measurements consisted of airblast and three-component particle velocity. The airblast measurements were made outside the house, at the front and at the rear. They consisted of both pressure-time records and peak noise (recorded with a sound level meter equipped with an impact noise analyzer). The particle velocity gages were located in the center of the living room floor. Both the airblast and particle velocity data were recorded on a portable oscillograph. The "noise source" consisted of 4.5 pounds of pentolite detonated in Building 314. The results of these measurements are summarized in Figure 5. For comparison purposes, an additional test is included. This is the "heel drop" test. The "heel drop" test was conducted in the living room of the test residence. Oscillograph records were made of the response of the seismic gages to a man standing at the center of the room, rising on his toes and allowing his weight to drop on his heels. The peak amplitudes of the particle velocity gages on the heel drop are about 3 times as high as the amplitudes recorded on the explosion test. To bring the airblast results into the realm of the commonplace, another type of comparison test was also conducted. The sound level measured seven feet from the "slamming" of the front door on a Dodge sedan was the same level as that indicated in Figure 5 (Ref. (2)).

In 1969, a detailed study of the "typical bombproof" shown in Figure 1 was begun. Although airblast measurements were included in this study, they were not the main emphasis. The gages were located 100 feet from the charge. The charge weights used were varied between 1 and 5 pounds, with the door open, closed, and partially closed. Figure 6 summarizes the airblast results from this test. The overall findings of this study can be summarized as follows:

(1) for charge weights between 1 and 5 pounds, the effect of totally closing the chamber was to reduce the airblast pressures measured 100 feet from the charge by an average of 22.8 dB (Ref. (1)).

(2) the installation of heavy steel doors on bombproofs should eliminate all noise and vibration complaints from neighboring private home owners.

Present Study

This present study has sought the answer to two other aspects of the noise problem: (1) what is the propagation law for the disturbance and (2) how do the sound pressure levels vary with charge weight at a fixed distance? Figure 7 is a synopsis of this present study. The charges were all pentolite cylinders and were initiated by means of an Engineer's Special Detonator.

Two types of airblast instrumentation were used in this study. The primary system consisted of B&K microphones and Celesco Corporation blast pressure transducers hard-wired into a magnetic tape recorder. The signals were played back on a Midwestern oscillograph. The frequency response of the system was 20 hz to 10 Khz. The secondary system consisted of General Radio Sound Level Meters equipped with Impact Noise Analyzers.

Measurements were made at four locations--three on NOL property, and the fourth at a private residence. The station at the private residence was equipped with a sound level meter/impact noise analyzer.

Multiple-peaked records were obtained at each position on almost every shot. Figure 8 contains tracings from one shot, and is typical of the type of records obtained on all the shots. In each case, the noise pulse begins as a well-defined series of shock waves, and is degraded into what appears to be a damped sinusoid.

Figures 9-15 are plots of the pressure-distance data recorded for each bombproof. Straight lines have been fitted to the "far-field" data. The data taken at the private residence are shown in these figures but have not been included in the straight line fit calculations. The author felt that these points should not be included in the fit because they would overly influence the results while themselves being strongly influenced by both the roughness of the terrain and the local meteorology. One assumption which has been made is that the pressure-distance decay slopes are independent of the charge weight for fixed door configurations in each bombproof. It is obvious from these plots that each bombproof appears to behave differently. Each has a characteristic pressure-distance decay slope and a pressure-charge weight scaling relationship. The decay slopes and weight-scaling exponents (scaled distance is obtained by dividing the distance by the charge weight raised to some appropriate exponent) are reported in Figure 16. With the exception of Bldg. 314, the decay is steeper than that caused by spherical spreading (R^{-1}). In Bldg. 314, for both the door open and door closed conditions, the decay was approximately that expected in the spreading of acoustic waves ($R^{-0.93}$ and $R^{-1.1}$).

The "noisiness" of the bombproofs can be characterized in at least two ways. The first is for a fixed charge weight, for example 2 lb, with the sound pressure level measured at a fixed distance (1000 feet in this example). The second method is to again use a fixed charge size (2 lb), and to measure the sound pressure level at the nearest non-government property line. The results of these calculations are presented in Figures 17 and 18. Thus, without a door, Bldg. 314 is the noisiest, while with a door, it is the next to the quietest. The door on Bldg. 324 produces a similar drop in the noise level.

In order to quantify the effect of doors on the sound pressure levels generated by bombproofs, let us define an attenuation or insertion loss, which is the difference in the sound pressure levels (in dB) between the door open operation and the door closed operation, for a given charge size, measured at the same distance. Because the

decay rates are nearly the same for the door open and door closed operations in Bldg. 314, the attenuation will not vary appreciably with distance. For a 2-lb charge, the insertion loss is 33.4 dB, while for a 4-lb charge it is 40.3 dB. In Bldg. 324, the door open and door closed decay slopes do vary greatly, so that the attenuation for this building will vary with distance. This is shown in Figure 19, which is for both 2- and 4-lb charges in Bldg. 324.

As a partial check on the data reported in this work, let us compare it with available previous results. For a 2-lb charge at 100 feet from Bldg. 324 Proctor (Ref. (1)) reports a pressure of 0.172 psi with the door open and 0.013 psi with the door closed. We measured 0.23 psi and .0119 psi under the same conditions. The maximum pressure reported by Sadwin and Swisdak (Ref. (3)) at a distance of 100 feet from Bldg. 331 was 0.36 psi for a 2-lb charge. We measured 0.56 psi under the same conditions. Reference (4) reports a peak of 132.5 dB (1.25×10^{-2} psi) at a position quite close to our third position for 2 lb fired in Bldg. 314 with the door open. At a nearby position we measured 134.5 dB (1.5×10^{-2} psi), and at a comparable distance (600 ft), Figure 9 indicates a pressure of 1.8×10^{-2} psi.

In summary, each bombproof behaves differently and should not be "lumped together" with any other bombproof. The observed far field sound pressure levels generally decay faster than acoustic waves subjected to spherical spreading only. The effect of a door on the noise produced by bombproofs seems to vary with the individual structure.

To generalize, however, might also be appropriate. In any explosive operation, there are certain things which can be done to reduce the noise level. Meterological observations are necessary; don't conduct tests under indicated conditions of ray focussing or enhancement. If the test chamber can be closed, do so. The terrain around the test area can also help. Trees and shrubs will help reduce the pressures in waves passing over them.

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1. Proctor, J. F., "Structural Analysis of NOL Explosion Test Facilities", NOLTR 69-84, 24 April 1969

2. Sadwin, L. D., Memorandum to Code 241, Subj:"NOL Produced Explosion Noise at 10803 Bornedale Drive, Airblast and Seismic Measurements", dated 21 December 1966

3. Sadwin, L. D. and Swisdak, M. M., Memorandum, Subj: "Bombproof Tests at Bldg. 331 of 29 August 1970", Dated 29 August 1970

4. Johnston, T. F., Code 221 memo to NOL Files, Subj: "Explosion Noise Tests of 14 September 1971", 20 September 1971

BUILDING NUMBER	TYPE OF CLOSURE	BUILDING VOLUME (ft^3)
314	DOOR	1750
317	NONE	1100
324	DOOR	2010
325	NONE	1560
331	NONE - HAS A CHIMNEY-MUFFLER	1200

FIG. 1 OPERATIONAL BOMBPROOFS AT NOL

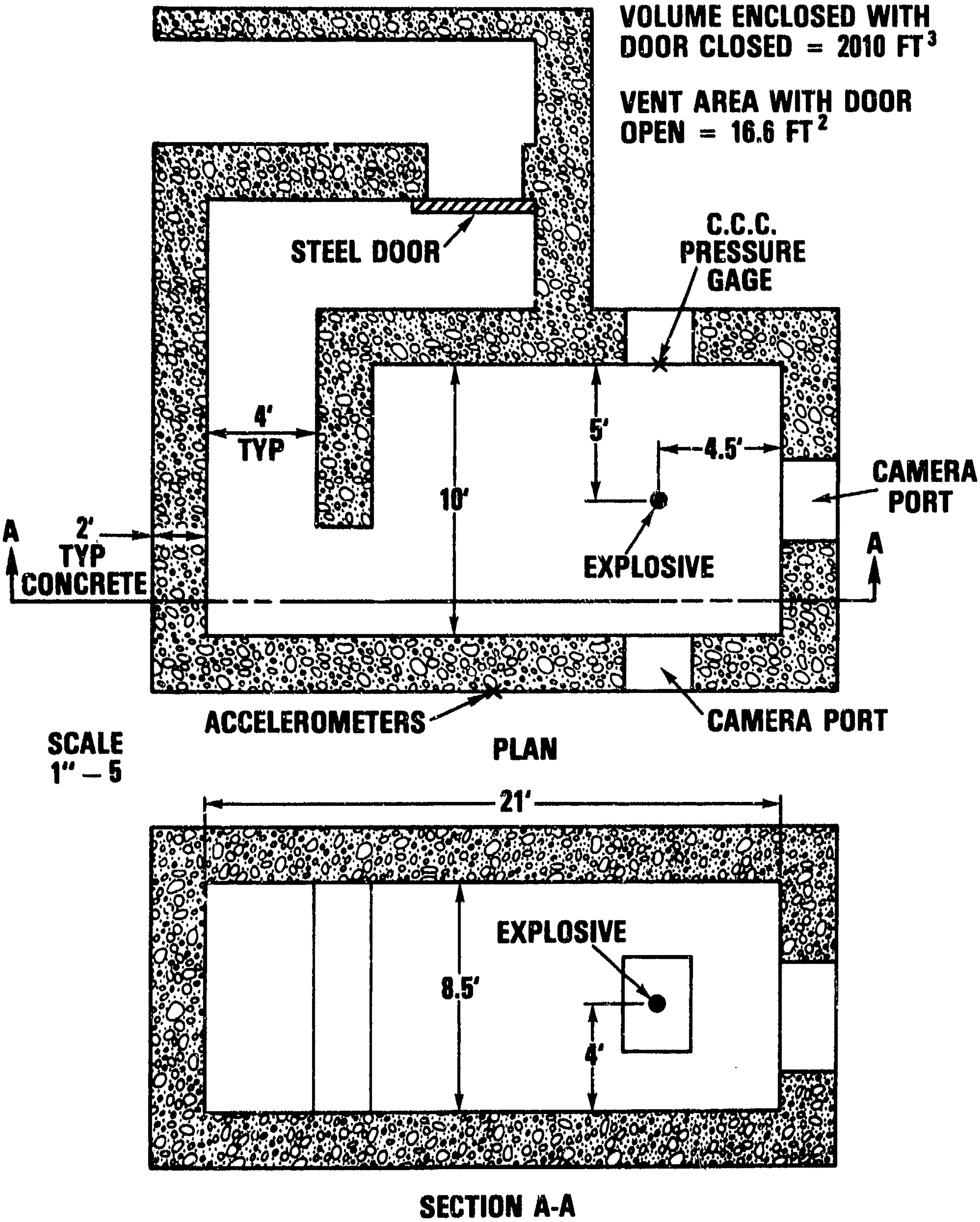

FIG. 2 CONFIGURATION OF TYPICAL BOMBPROOF

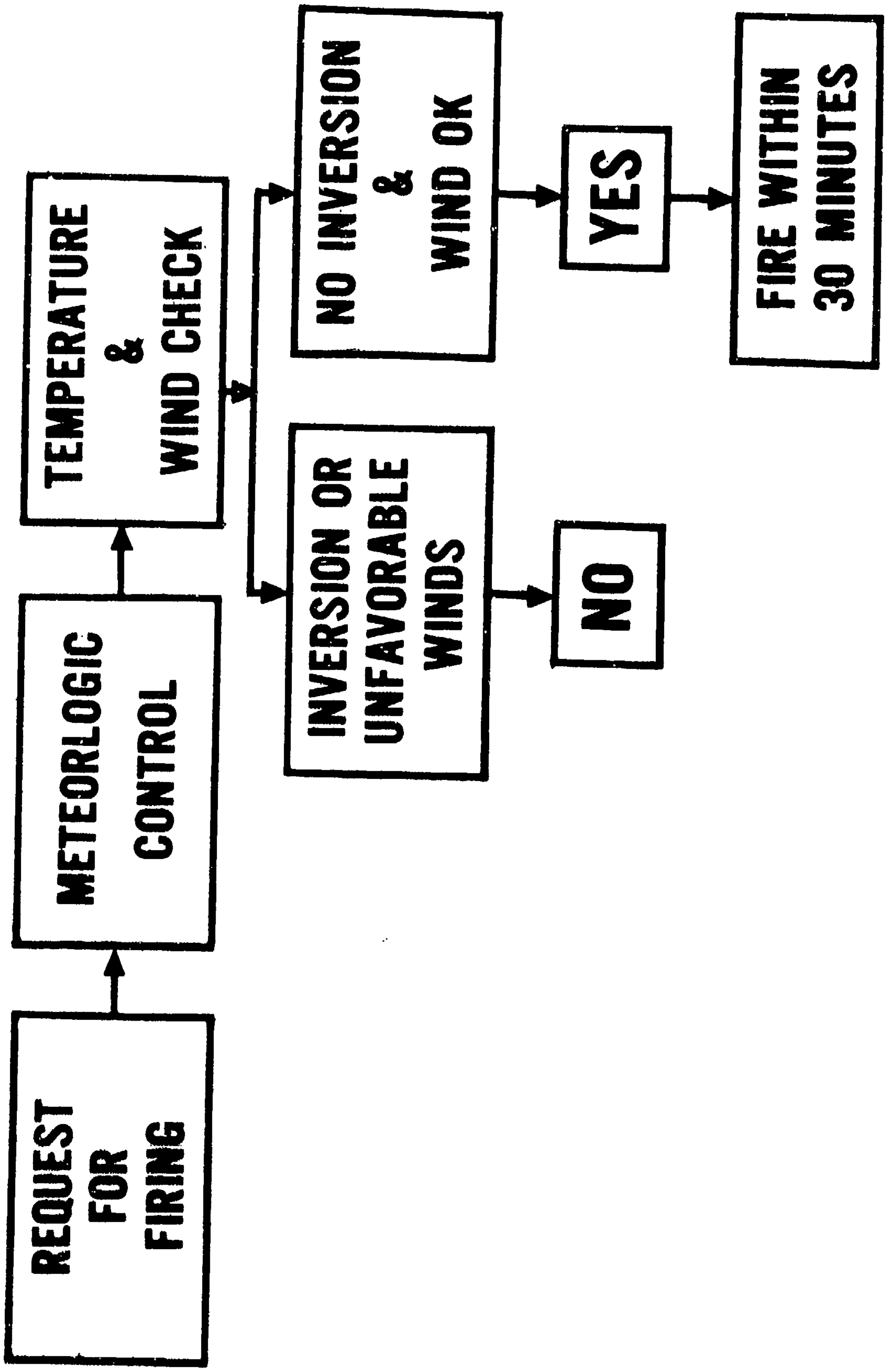

FIG. 3 NOISE CONTROL SYSTEM

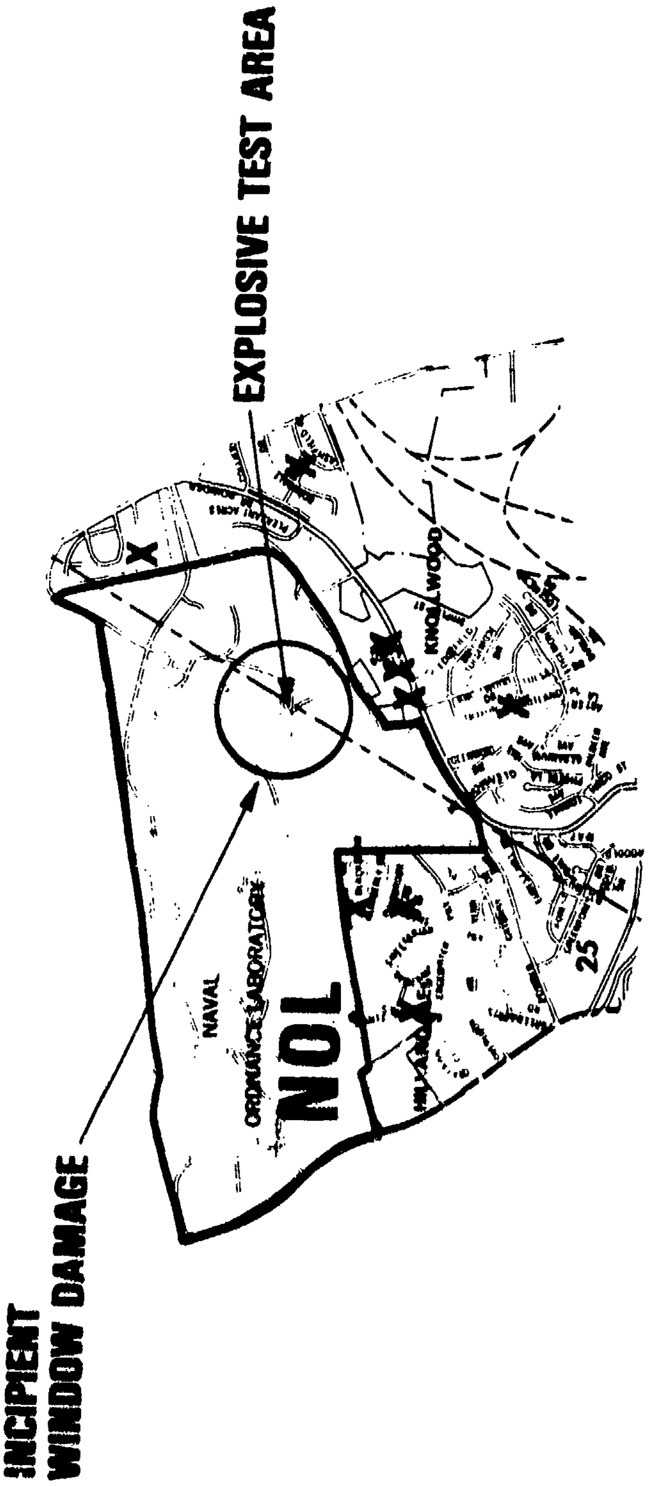

FIG. 4 NOL AND ITS SURROUNDINGS

- 4½ LB EXPLOSIVE IN BOMB PROOF
- MEASUREMENTS AT 3000 FT DISTANCE

AT HOUSE

BLAST PRESSURE	0.0007 PSI (MAX)
FLOOR VIBRATION	0.046 IN/SEC (MAX)
(HEEL DROP FLOOR VIBRATION)	0.16 IN/SEC (MAX)

FIG. 5 RESIDENCE TEST (NOV. '66)

CHARGE WEIGHT (POUNDS)	DOOR	AVERAGE OVERPRESSURE AT 100 FEET (psi)
1	OPEN	8.43×10^{-2} (149.2)*
1	CLOSED	5.6×10^{-3} (125.7)
2	OPEN	1.72×10^{-1} (155.4)
2	CLOSED	1.27×10^{-2} (132.8)
5	OPEN	3.15×10^{-1} (160.7)
5	CLOSED	2.41×10^{-2} (138.3)

****NUMBERS IN ( ) ARE PRESSURES IN dB, RE: 2×10^{-5} N/M^2***

FIG. 6 SOUND PRESSURE MEASUREMENTS OUTSIDE BUILDING 314

BUILDING	DOOR	CHARGE WEIGHT AND SIZE 0.5 LB 2 x 2.68*	1.0 LB 2 x 5.36*	2.0 LB 4¼ x 2.37*	4.0 LB 4¼ x 4.74*
314	OPEN			X	X
314	CLOSED			X	X
317	NONE	X	X		
324	OPEN			X	X
324	CLOSED			X	X
325	NONE	X		X	
331	MUFFLER	X		X	

* DIAMETER X LENGTH (BOTH IN INCHES)

FIG. 7 SUMMARY OF TEST PROGRAM

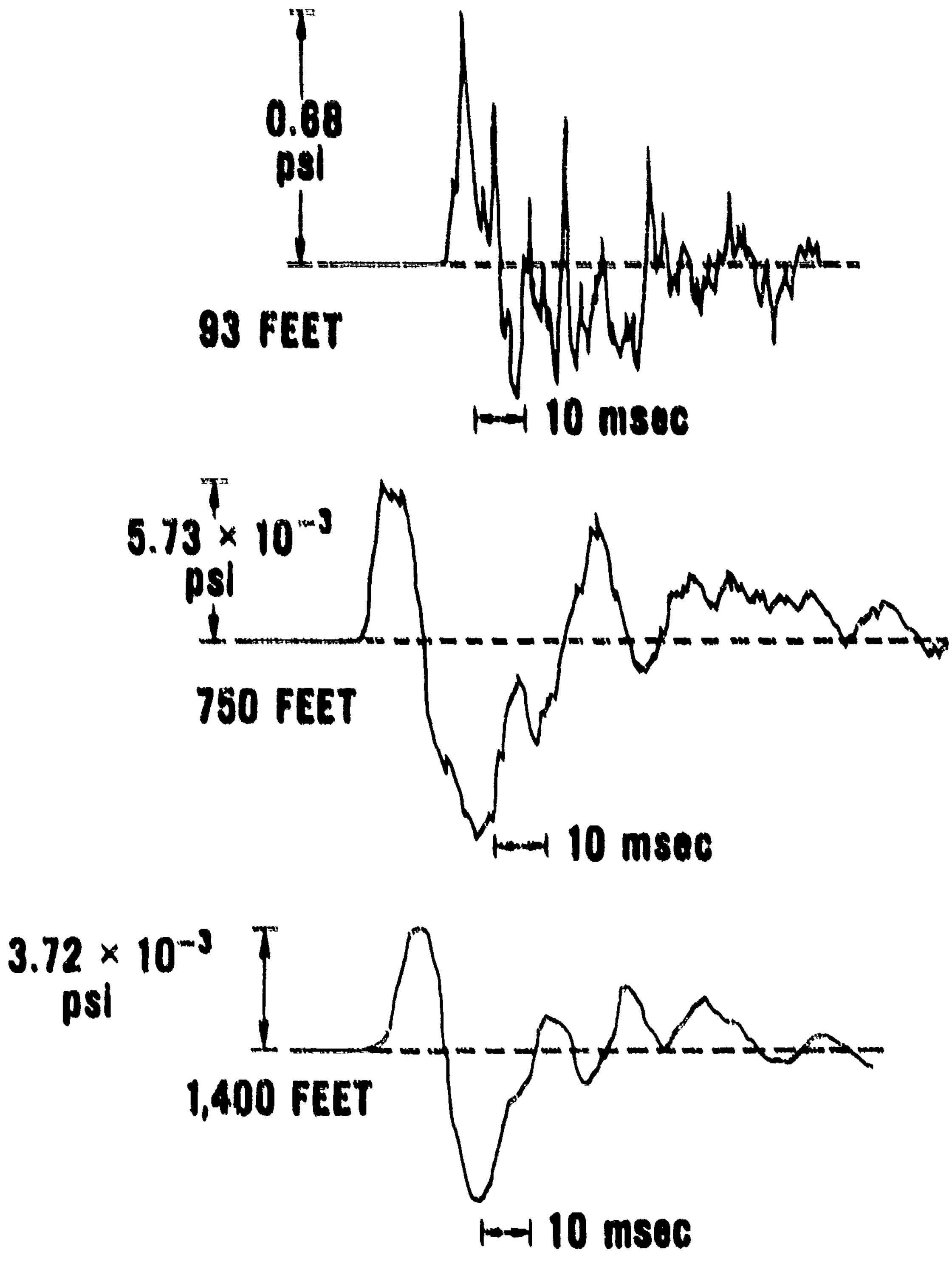

FIG. 8 REPRESENTATIVE WAVE FORMS FROM FIRING 2 POUNDS OF EXPLOSIVE IN BLDG. 325

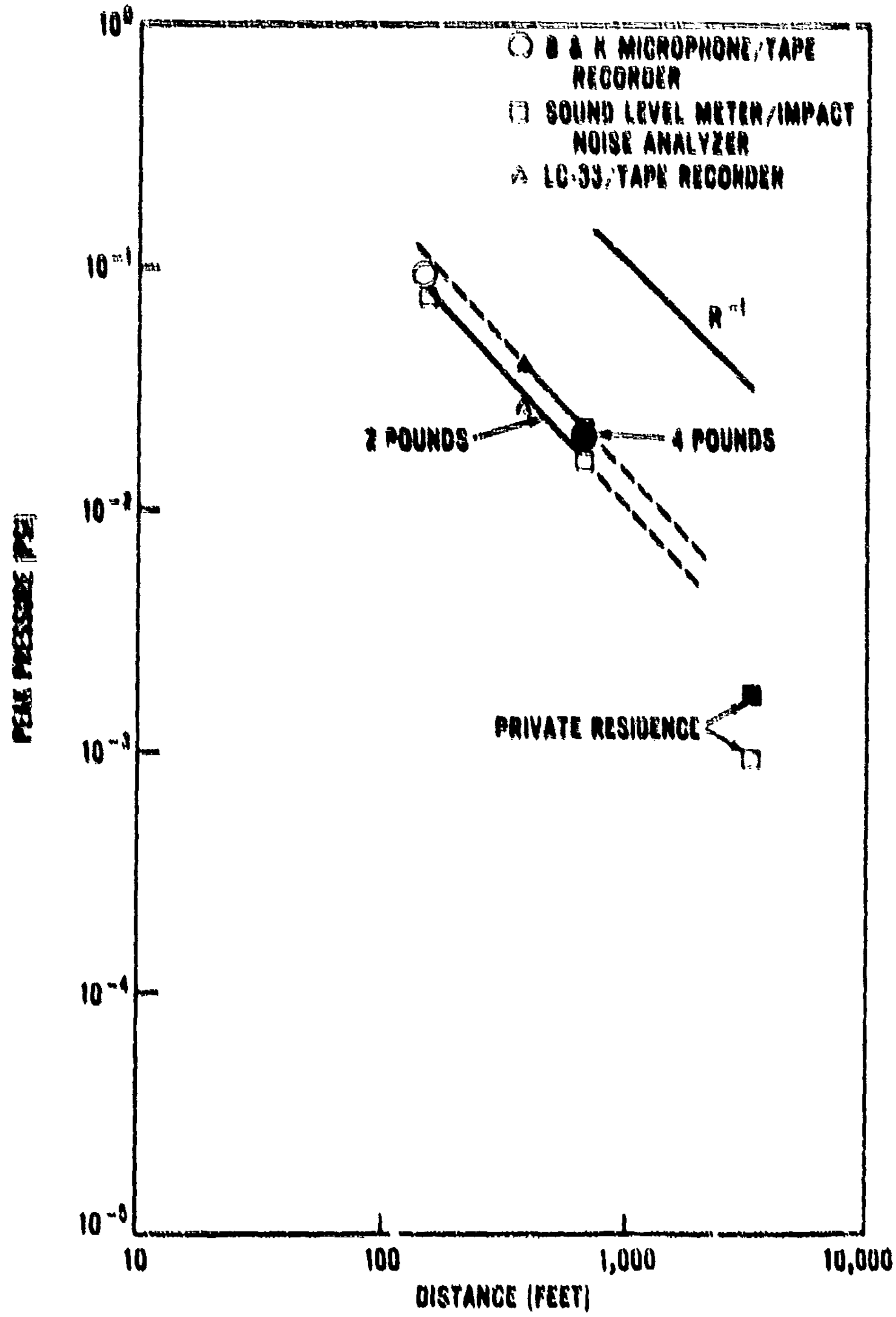

FIG. 9 PRESSURE VS DISTANCE FOR BLDG. 314 WITH DOOR OPEN FOR TWO CHARGE WEIGHTS

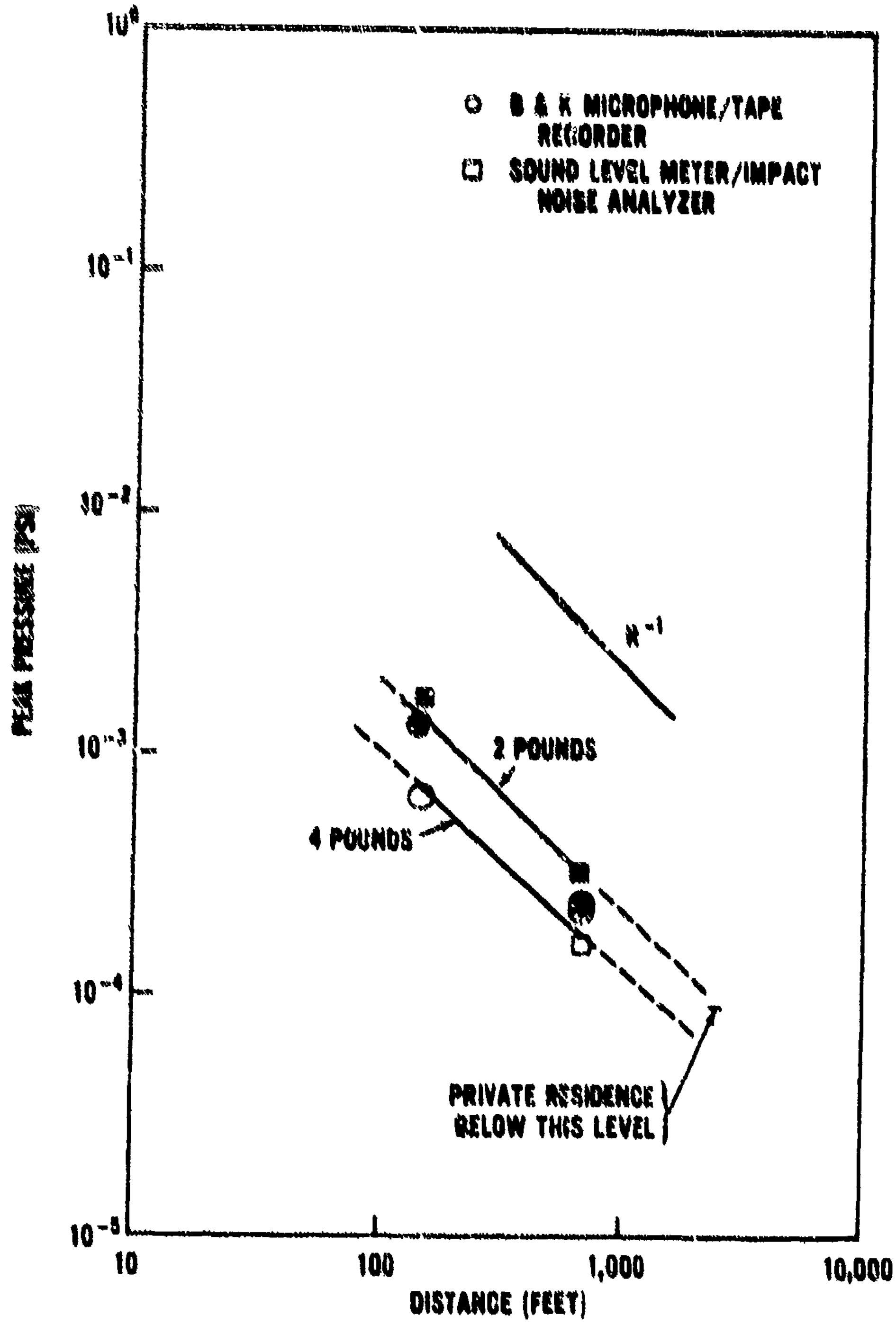

FIG. 10 PRESSURE VS DISTANCE FOR BLDG. 314 WITH DOOR CLOSED FOR TWO CHARGE WEIGHTS

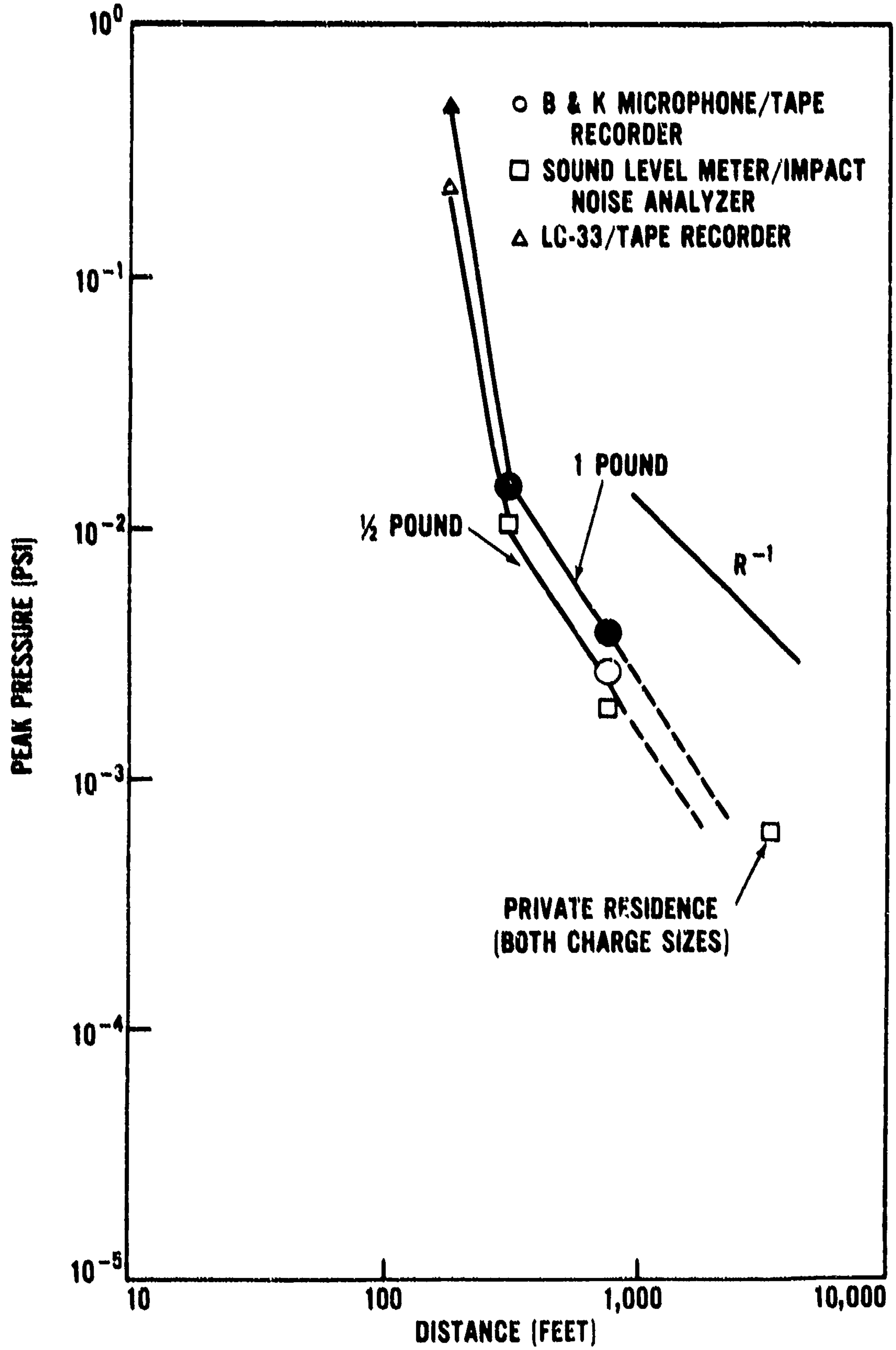

FIG. 11 PRESSURE VS DISTANCE FOR BLDG. 317 FOR TWO CHARGE WEIGHTS

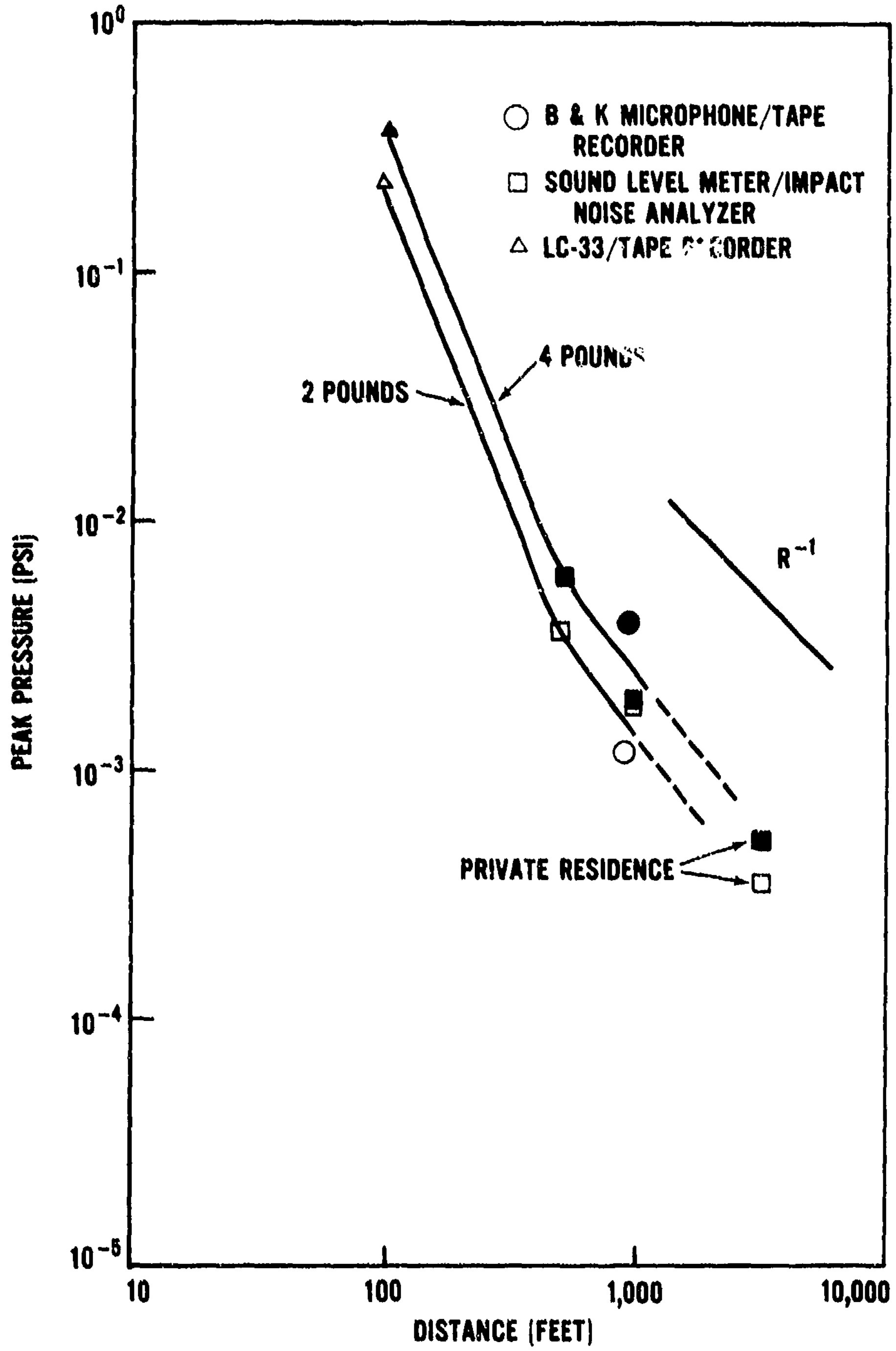

FIG. 12 PRESSURE VS DISTANCE FOR BLDG. 324 WITH DOOR OPEN FOR TWO CHARGE WEIGHTS

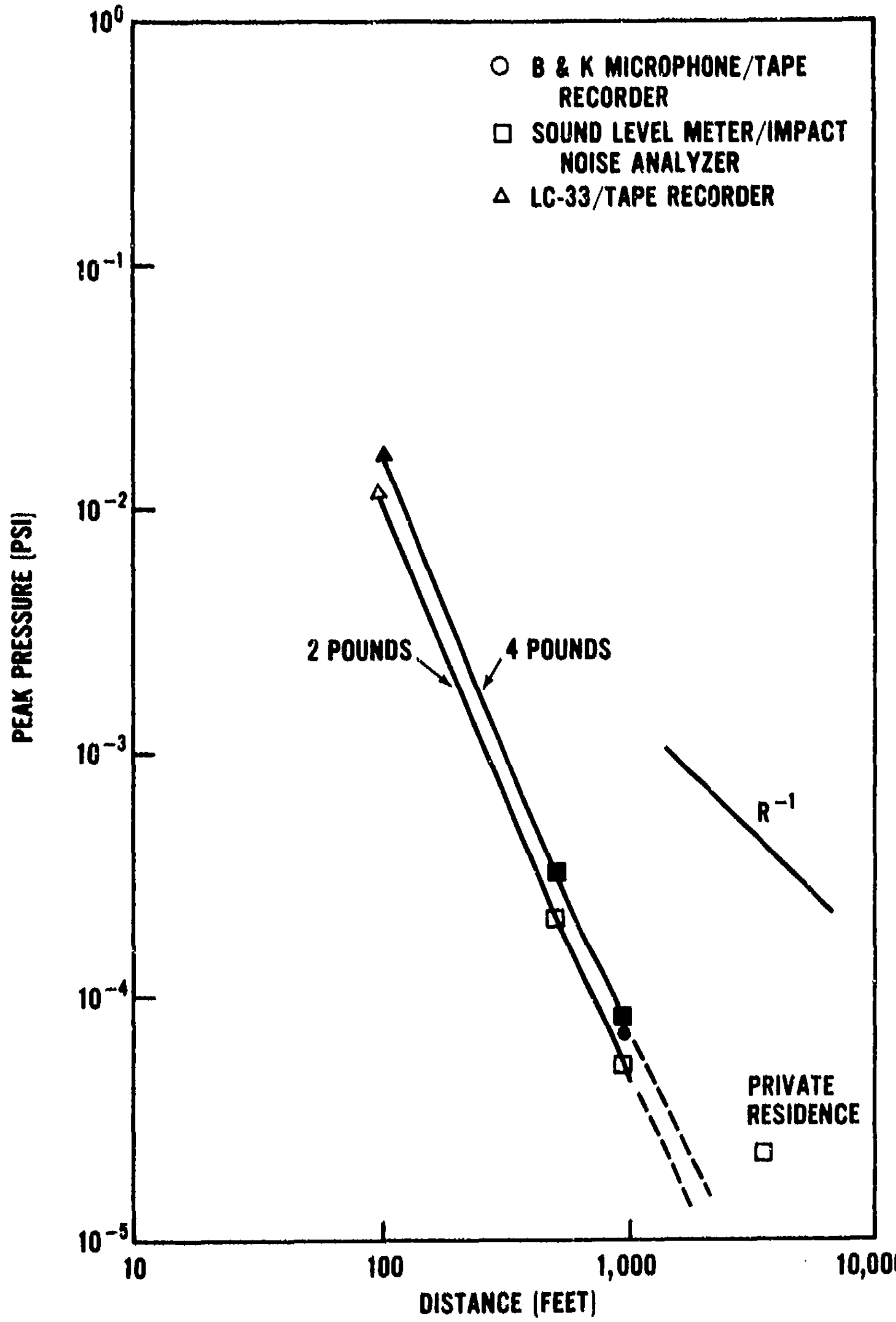

FIG. 13 PRESSURE VS DISTANCE FOR BLDG. 324 WITH DOOR CLOSED FOR TWO CHARGE WEIGHTS

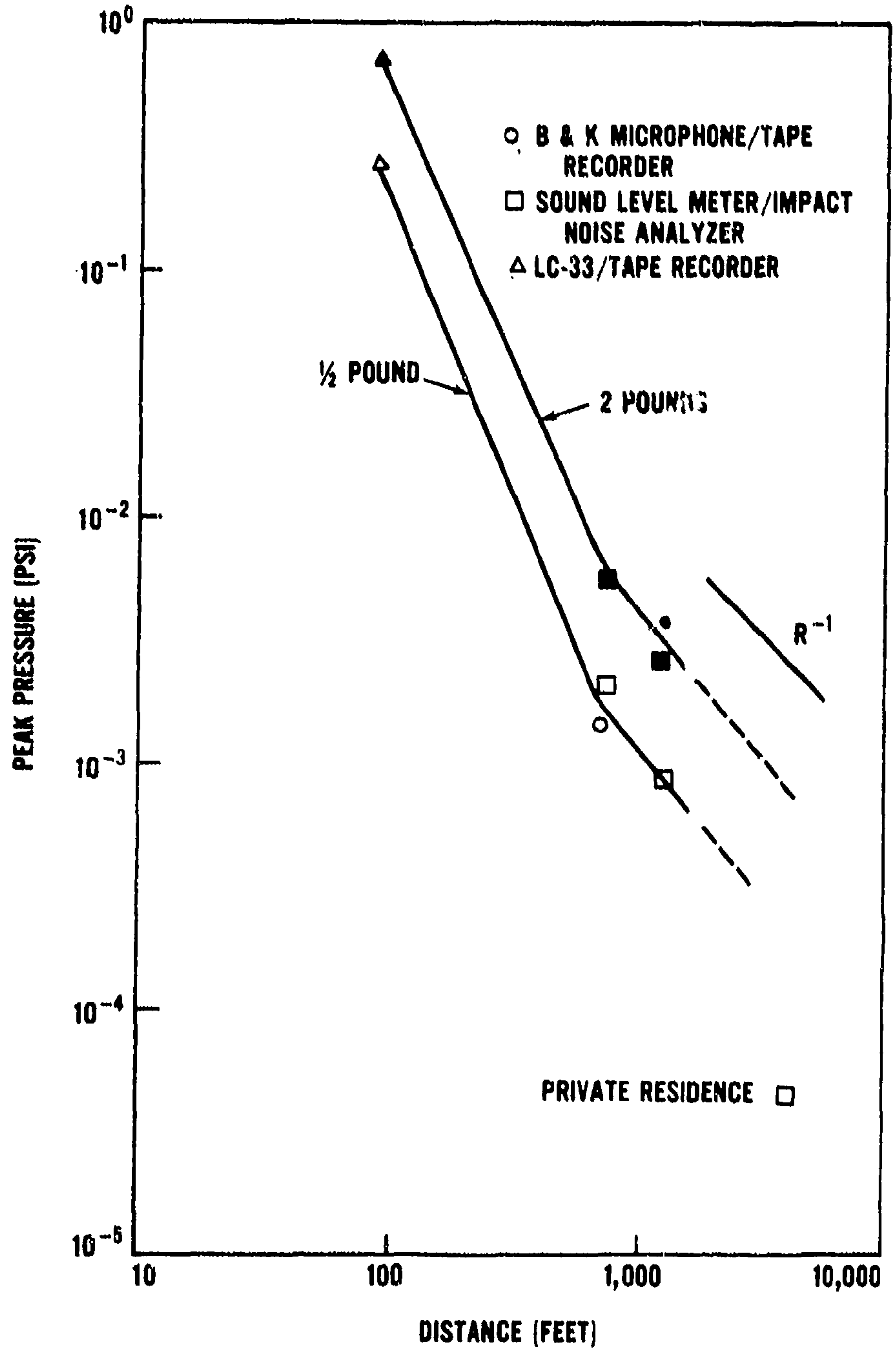

FIG. 14 PRESSURE VS DISTANCE FOR BLDG. 325 FOR TWO CHARGE WEIGHTS

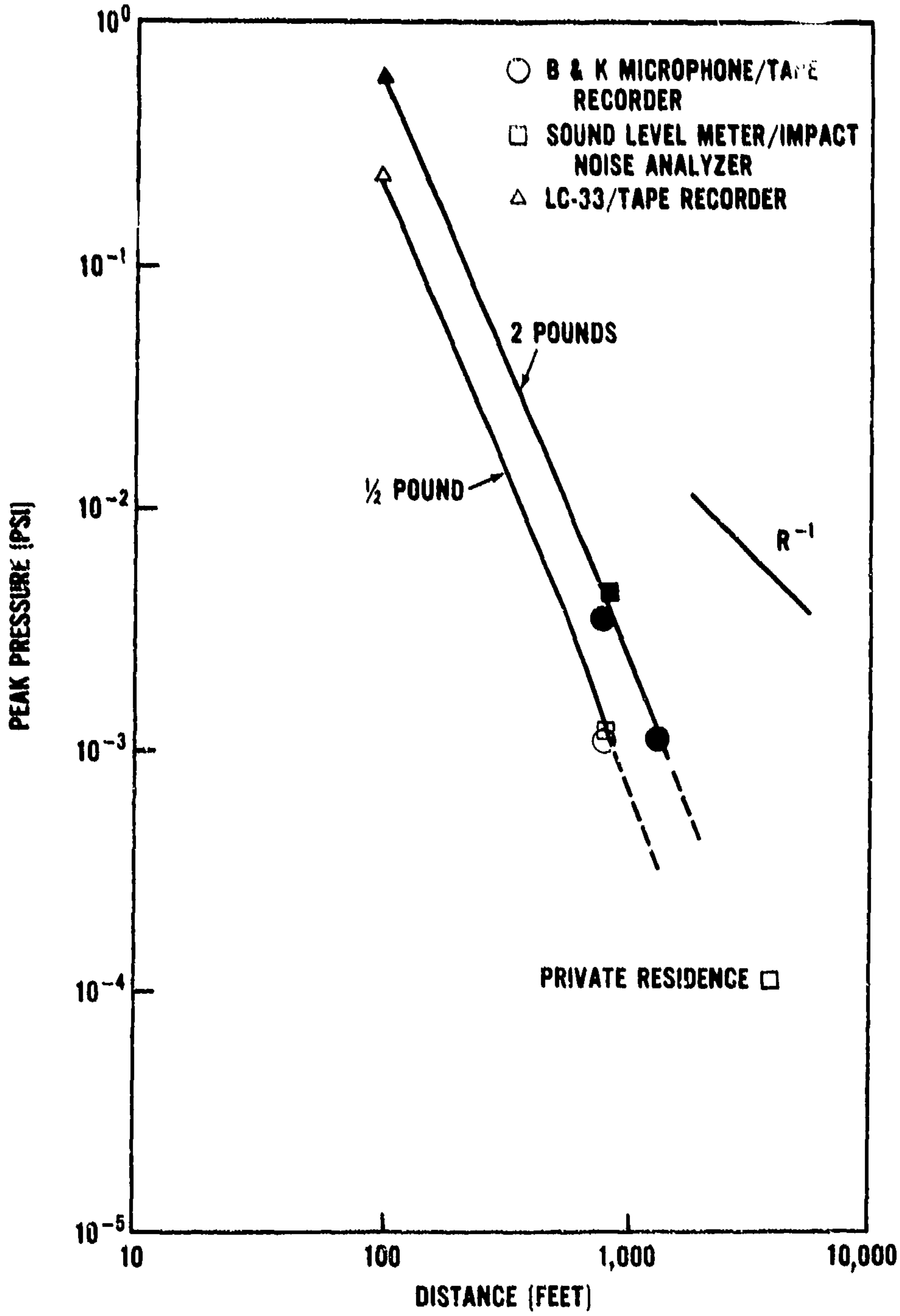

FIG. 15 PRESSURE VS DISTANCE FOR BLDG. 331 FOR TWO CHARGE WEIGHTS

BUILDING	DOOR	FAR FIELD PRESSURE VS DISTANCE (1) DECAY SLOPE (x)	FAR FIELD WEIGHT SCALING (2) EXPONENT (n)
314	OPEN	−1.1	.64
314	CLOSED	− .93	.28
317	NONE	−1.54	.67
324	OPEN	−1.3	.76
325	NONE	−1.22	.69
331	MUFFLER	−2.74	.38

(1) FOR $P^+_{max} \sim R^x$, WHERE P^+_{max} IS THE PEAK POSITIVE PRESSURE (psi) AND R IS DISTANCE IN FEET.

(2) FOR SCALING OF THE FORM $P^+_{max} \sim R/W^n$, WHERE P^+_{max} AND R ARE THE SAME AS ABOVE AND W IS THE CHARGE WEIGHT IN POUNDS.

FIG. 16 DECAY SLOPES AND WEIGHT SCALING EXPONENTS

BUILDING	DOOR	PEAK PRESSURE (psi)	PEAK PRESSURE (dB)	NOISINESS RANKING (1 = LOUDEST)
314	OPEN	1.01×10^{-2}	130.9	1
314	CLOSED	2.22×10^{-4}	97.7	6
317	NONE	5.8×10^{-3}	126.1	2
324	OPEN	1.49×10^{-3}	114.3	5
324	CLOSED	4.70×10^{-5}	84.2	7
325	NONE	4.18×10^{-3}	123.2	3
331	MUFFLER	2.36×10^{-3}	118.3	4

FIG. 17 NOISINESS RANKING FOR 2 POUND CHARGES AT 1,000 FEET

BUILDING	DOOR	DISTANCE (FT)	PEAK PRESSURE (psi)	(dB)	NOISINESS RANKING (1 = LOUDEST)
314	OPEN	810	1.29×10^{-2}	133.0	1
314	CLOSED		2.72×10^{-4}	99.5	6
317	NONE	990	5.8×10^{-3}	126.1	2
324	OPEN	1220	1.17×10^{-3}	112.2	4
324	CLOSED		3.12×10^{-5}	80.7	7
325	NONE	1390	2.78×10^{-3}	119.7	3
331	MUFFLER	1570	6.5×10^{-4}	107.1	5

FIG. 18 NOISINESS RANKING FOR 2 POUND CHARGES AT NEAREST NON-GOVERNMENT PROPERTY

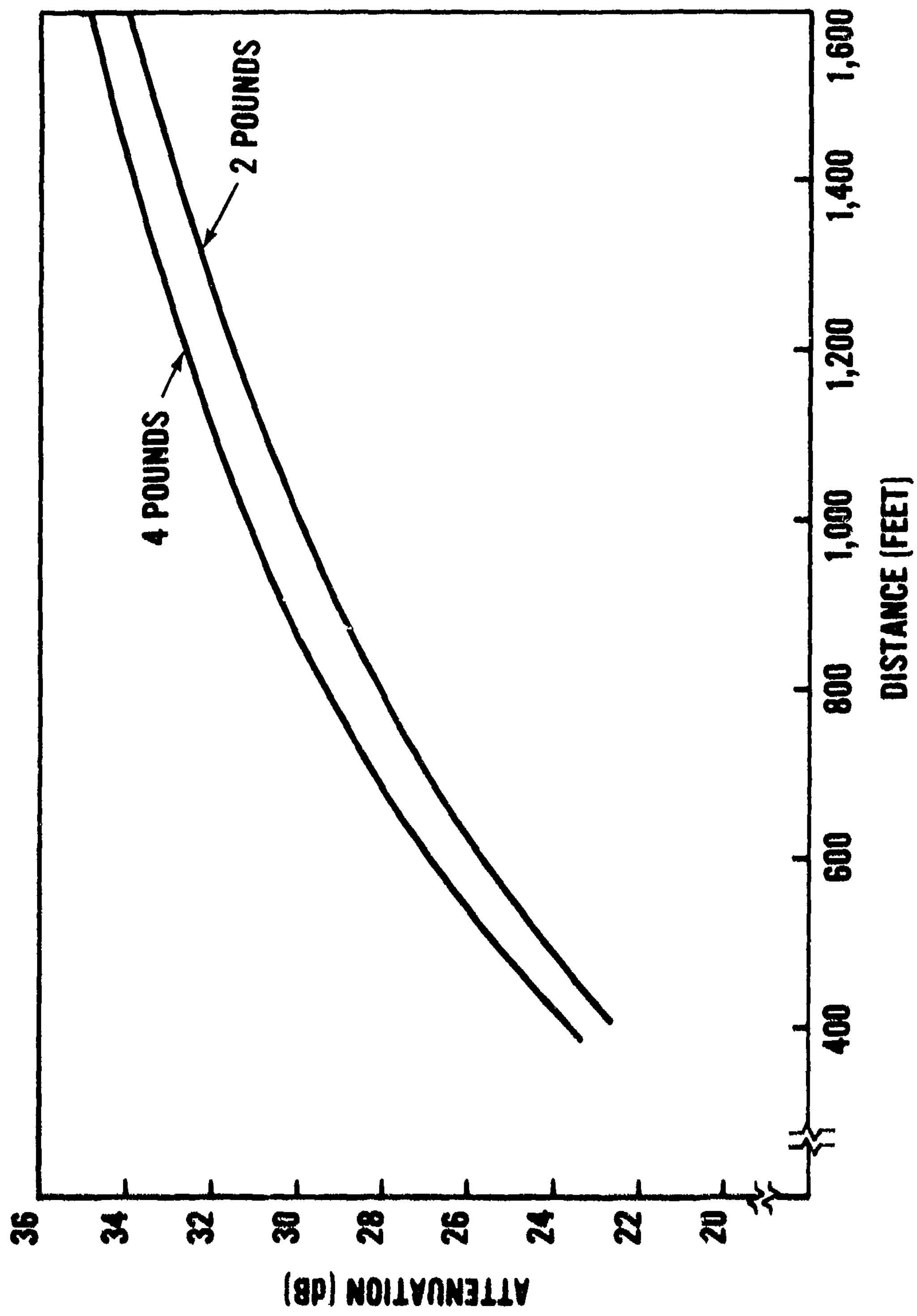

FIG. 19 ATTENUATION INTRODUCED BY DOOR VS DISTANCE FOR BLDG. 324

PEAK NOISE PREDICTED AT LONG DISTANCES BY A UNIFIED THEORY OF EXPLOSIONS

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ABSTRACT

A recently published unified theory of explosions (UTE)/(NOLTR 72-209*) predicts and explains why pressures measured at long distances from explosions are always less than predicted by early theory or some machine calculations.

In UTE a comprehensive and strong separation of blast energy is made into a decreasing "promptly available" fraction Y and a growing "delayed" fraction Q as the shock progresses. Q not only includes non-linear shock compression but can also include many other "dissipative" modes such as gross atmospheric nonuniformity, local turbulence and thermal cells, reflection and impedance from ground surfaces. Scaling still requires $P \sim Y^{1/3}/R$ at long distances, but it is shown that $Y \sim 1/R$ from non-linear compression alone and however weak the blast becomes. Hence the noise pollution (pressure) must decrease at least as fast as $P \sim 1/R^{4/3}$. If other modes of loss occur, the noise will decrease even faster. They also suggest means of noise-abatement.

Data from NOLTR 72-209 confirmed the weak shock UTE predictions over a spread of 10^6 times in dissipation Q and 100 times in overpressure P. This paper presents experimental data which agree with the UTE predictions over a range of 10^{15} in Q and 10^6 in overpressure, well within experimental uncertainty.

* Introduction to a Unified Theory of Explosions (UTE) by Francis B. Porzel, NOLTR 72-209, Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland 20910

Characteristics of Shock Waves in Water Near Underground Explosions

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There have been three nuclear explosions underground at Amchitka, an island in the western Aleutian Islands off Alaska. These were Long Shot, an 80 kiloton shot fired at a depth of 2350 ft in 1965; Milrow, an approximately 1 megaton shot fired at a depth of 4000 ft in 1969; and Cannikin, a shot of somewhat less than 5 megatons fired at a depth of 5875 ft in 1971. Amchitka is a long, narrow island, nowhere broader than 5 miles, so that a shot anywhere under the island is near the water of the ocean and the many ponds and streams that flow down to the ocean.

The immediate effects as seen by photography were spectacular (Figure 1), consisting of widespread whitening and spraying of the sea and of the ponds and streams on land. Spouts or geysers appeared, reaching heights of tens of meters. The measurements of ground motion and water pressures accompanying these phenomena are the source of the insights outlined in this paper.

Ground shock in the absence of water has been a matter of study since the first underground nuclear detonation in 1957, and is amply reported in the literature; see, for instance, Adams et al. (1961), Sauer et al. (1964), or Murphy and Lahoud (1969). On the other hand experience with ground-shock-induced water pressures is scarce, and is essentially limited to the Amchitka experience.

Figure 2 is typical of the surface ground motion measurements resulting from such underground explosions. This record, taken on Cannikin at a horizontal distance from surface zero of 4200 m, is dominated by underground spall, a separation in the underlying rock caused by reflection in tension of the shock wave from the free surface. This spall results in a period of free fall and a second and stronger acceleration pulse as the spall surface closes under the gage. On land, spall is common to horizontal distances equal to several shot depths, but not past the distance at which a peak vertical acceleration of 1 g occurs. Particularly to be noted in this record is the slow rise of the initial signal, over 100 ms in the case of velocity.

bottom. This is because the return time of the first rarefaction reflected from the surface is less than the rise time of the velocity pulse. As a result the peak pressure is cut off early and does not reach its full potential implied in Equation (1). This principle can be generalized to produce the analysis shown in Figure 6. Here the top line indicates the peak water pressure to be expected at various distances from the Milrow surface zero, at places where the water is at least 180 ft (55 m) deep, that being the depth at which the return rarefaction coincides with the peak velocity of the bottom. The other curves are pressures to be found at lesser depths. Each one is lower than the top curve in proportion to y/180, where y is the depth of the gage. Also shown on this figure are measured peak pressures.

In shallow water reverberations are so frequent that the use of Equation (2) would be tedious and subject to cumulative error; however, an approximation is available. If one assumes that the water moves as a whole, the pressure at the bottom of the water is equal to the mass per unit area times the acceleration of the water, or

$$P = \rho da \tag{3}$$

Detailed calculations on sample wave forms has indicated that this approximation follows the results of the use of the more exact Equation (2) closely if rise times are long relative to reverberation times, but averages through the oscillations that result from fast rise times. Thus in Figure (3) the first pulse is the result of a slowly changing acceleration pulse and is itself simple; the second pulse is the result of a sharply rising spall closure pulse and is very oscillatory.

The negative phase of the pressure wave is, as we have seen, complicated by water spall or cavitation. Wentzell et al.'s (1969) classical treatment of the cavitation due to shock pulses reflected from the sea surface indicates that under certain circumstances water spall occurs. For a triangular wave form,

$$P(t) = P_m(1 - t/t_o)$$

the spall depth is

$$y_s = \frac{P_o}{(2P_m/ct_o) - \rho g} \tag{4}$$

where P_o is atmospheric pressure. Obviously the spall depth, y_s, must be less than the water depth, d; but if not there is still a separation at the sea floor in most cases because of the gross mismatch of seismic impedances there.

At Amchitka this ground shock was refracted at the sea floor into the water, carrying with it this long rise time as the first of several differences from shocks generated directly in the water. There, rise times are essentially instantaneous (Cole, 1948). A second important difference is that at Amchitka the shock travels to the surface along a path that is at a considerable angle with the horizontal, and the ray path after refraction into the water cannot be over 25° from the vertical. In water, on the other hand, nearly horizontal ray paths are common.

A resulting pressure in shallow water is shown in Figure 3. (Pond DP was 45 cm deep and 2100 m from Cannikin surface zero.) The signal is much like the acceleration signal of Figure 2, except for the complexity of the spall closure signal. Typical signals in deep water are shown in Figure 4. (Station W8 was in water 25 m deep and 2600 m from Milrow surface zero.) The shape of the pressure pulse in this instance is intermediate between the wave shape of the acceleration and velocity pulses. In neither shallow nor deep water is the pressure pulse related directly to the velocity pulse by the usual relationship

$$P = \rho c u \tag{1}$$

However, this is not surprising, since this is a relationship that holds only for simple waves, which is to say waves travelling in one direction only.

The nearly vertical ray paths result in multiple reverberations of the energy trapped in the water. Analysis of these reverberations results in the expression

$$P = \sum_{0}^{\infty} (-R)^n \left[f\left(t + \frac{y}{c} - \frac{2nd}{c}\right) - f\left(t - \frac{y}{c} - \frac{(2n+1)d}{c}\right)\right] \tag{2}$$

where y is the depth below the surface, d is the total depth of water, c is the velocity of sound in water, and R is the reflection factor at the bottom (≈ .7, see Merritt, 1969). The input pressure wave shape f(t) is that which would be expected if the water were very deep, and is equal to $\rho c u(t)$, where u(t) is the vertical velocity of the sea floor. (For a discussion of the simplifying assumptions behind Equation (2) see Merritt, 1973).

Figure 5 is an example of how well this theory accounts for the observed wave shapes. The first positive pulse is very well accounted for, but as might be expected the theory breaks down at the point in the negative phase where it calls for negative overpressures strong enough to cause cavitation. In Figure 4 the peak pressure in the water comes before the peak vertical velocity of the

Wentzell et al. prescribe a series of water spalls at greater depths. My analysis finds the region below the first spall to be a region of continuous spall, or bulk cavitation, because the boundary condition at the spall surface is P = 0, not $P = P_0$ as it is at the sea surface where the first reflection takes place. But whether it be intermittent or continuous spall, such a region is very damaging to biological organisms, to which it is a region of explosive decompression. Figure 7 shows that the phenomenon of bulk cavitation occurred over a large area on Cannikin; a similar figure for Milrow, not given here, would indicate that this phenomenon occurred only in a small area on Milrow.

In summary, there are distinct differences in water pressures caused by explosions in the underlying rock as at Amchitka from the classically studied case of explosions in the water itself. Propagation nearly perpendicular instead of nearly parallel to the water surface changes a single interaction surface cutoff to a multiple interaction from repeated reverberations. Moreover, the slow rises characteristic of shocks that have travelled any distance through rock or soil result in water pressures with slow rises. After interaction with the surface, wave forms do not have sharp leading and trailing edges, and their amplitudes are not simply related to the accompanying particle velocities. Peak pressures decrease approximately linearly in amplitude, not duration, as the gaging point approaches the water surface.

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FIG. 1 SURFACE EFFECTS OF CANNIKIN.

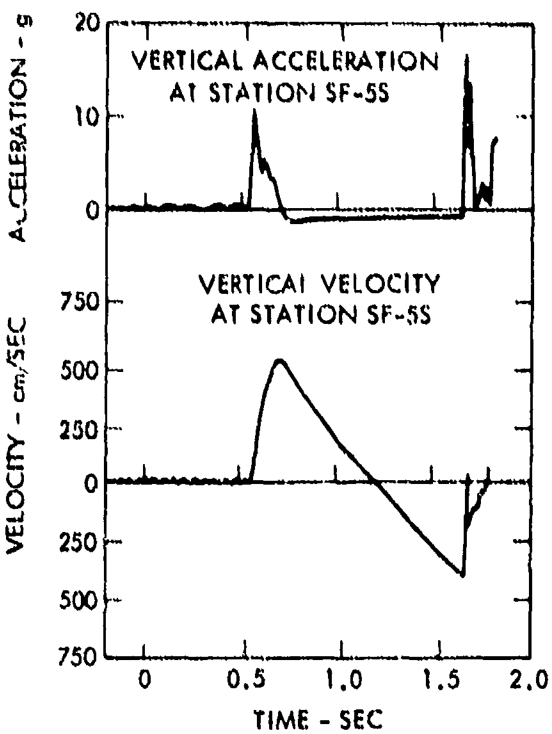

FIG. 2 VERTICAL ACCELERATION AND VELOCITY MEASURED AT CANNIKIN STATION SF-5S.

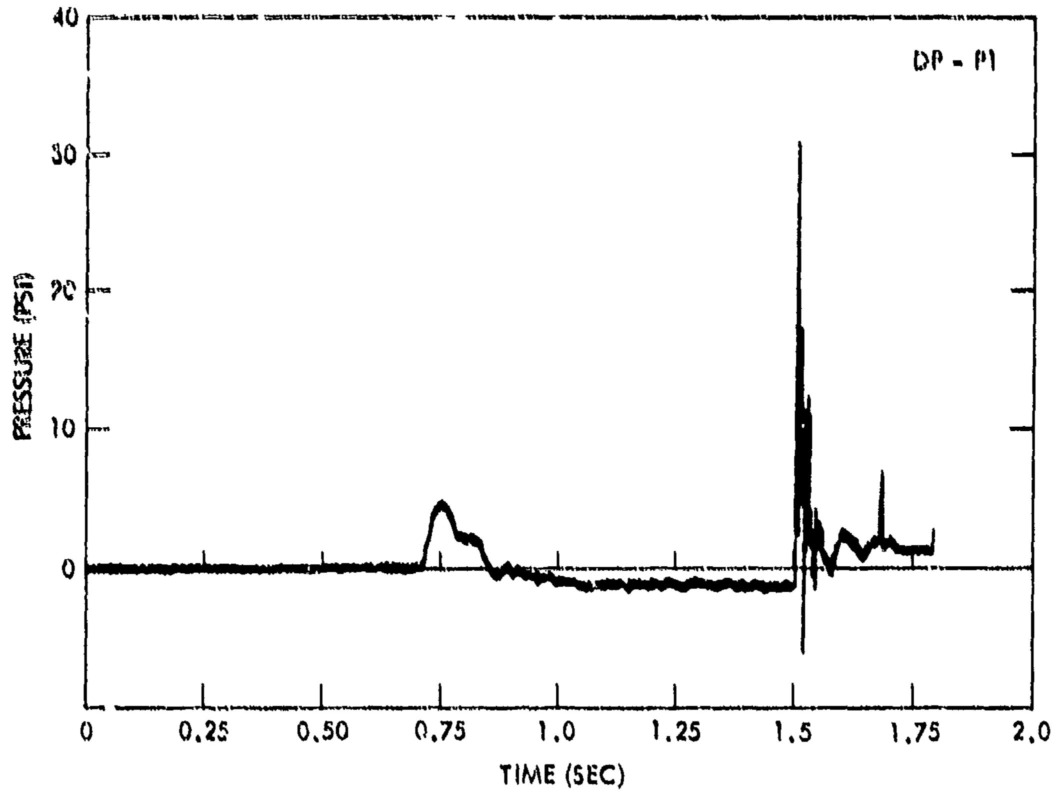

FIG. 3 PRESSURE IN LAKE DP, STATION DP-1.

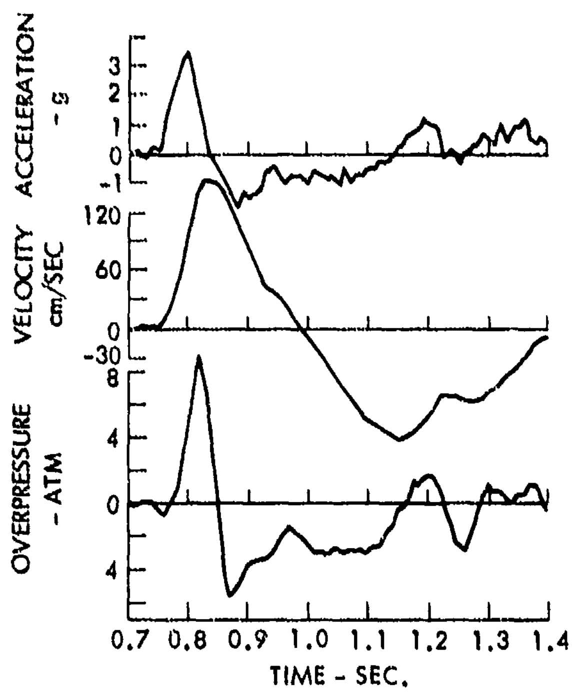

FIG. 4 VERTICAL ACCELERATION AND VELOCITY AND BOTTOM OVERPRESSURE MEASURED AT MILROW STATION W8 .

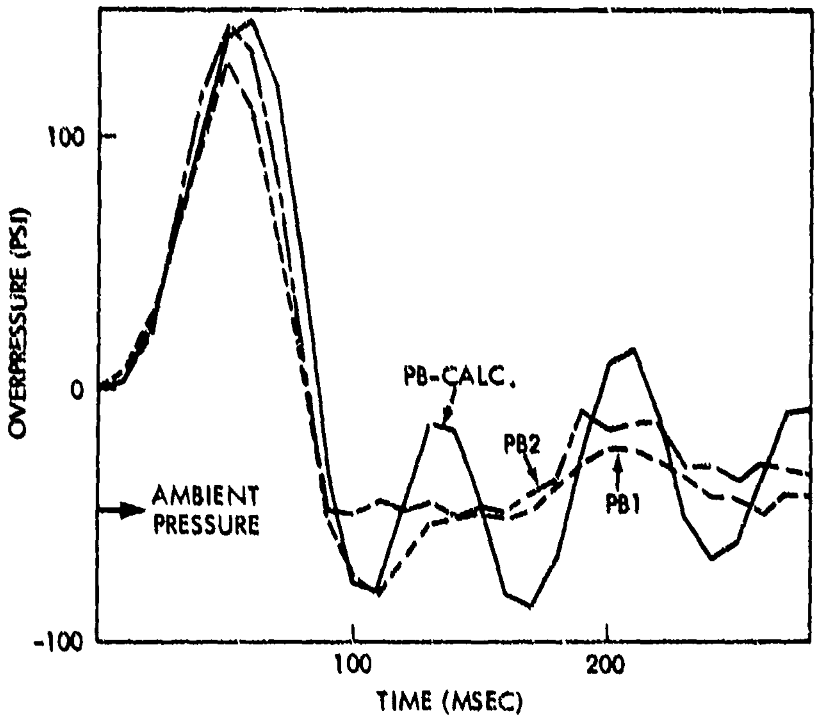

FIG. 5 COMPARISON OF MEASURED AND CALCULATED WAVEFORMS, STATION W8 BOTTOM PRESSURES.

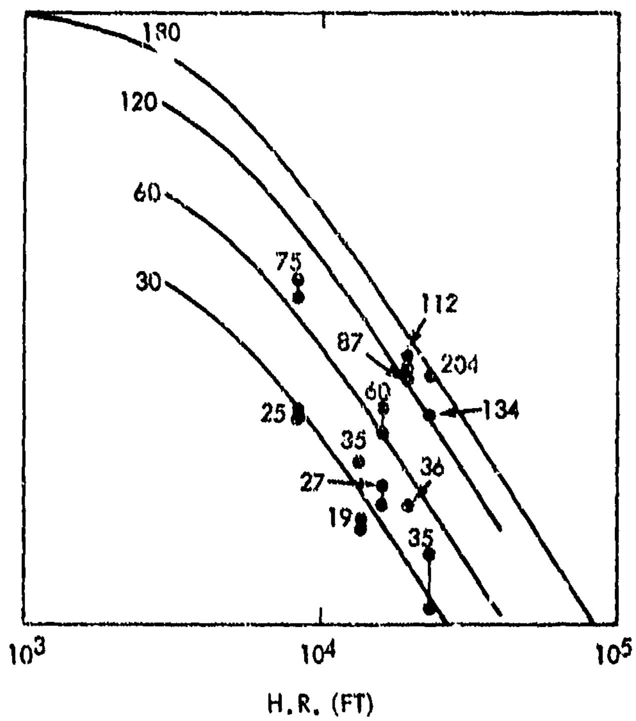

FIG. 6 MILROW WATER PRESSURES VERSUS HORIZONTAL RANGE AND DEPTH.

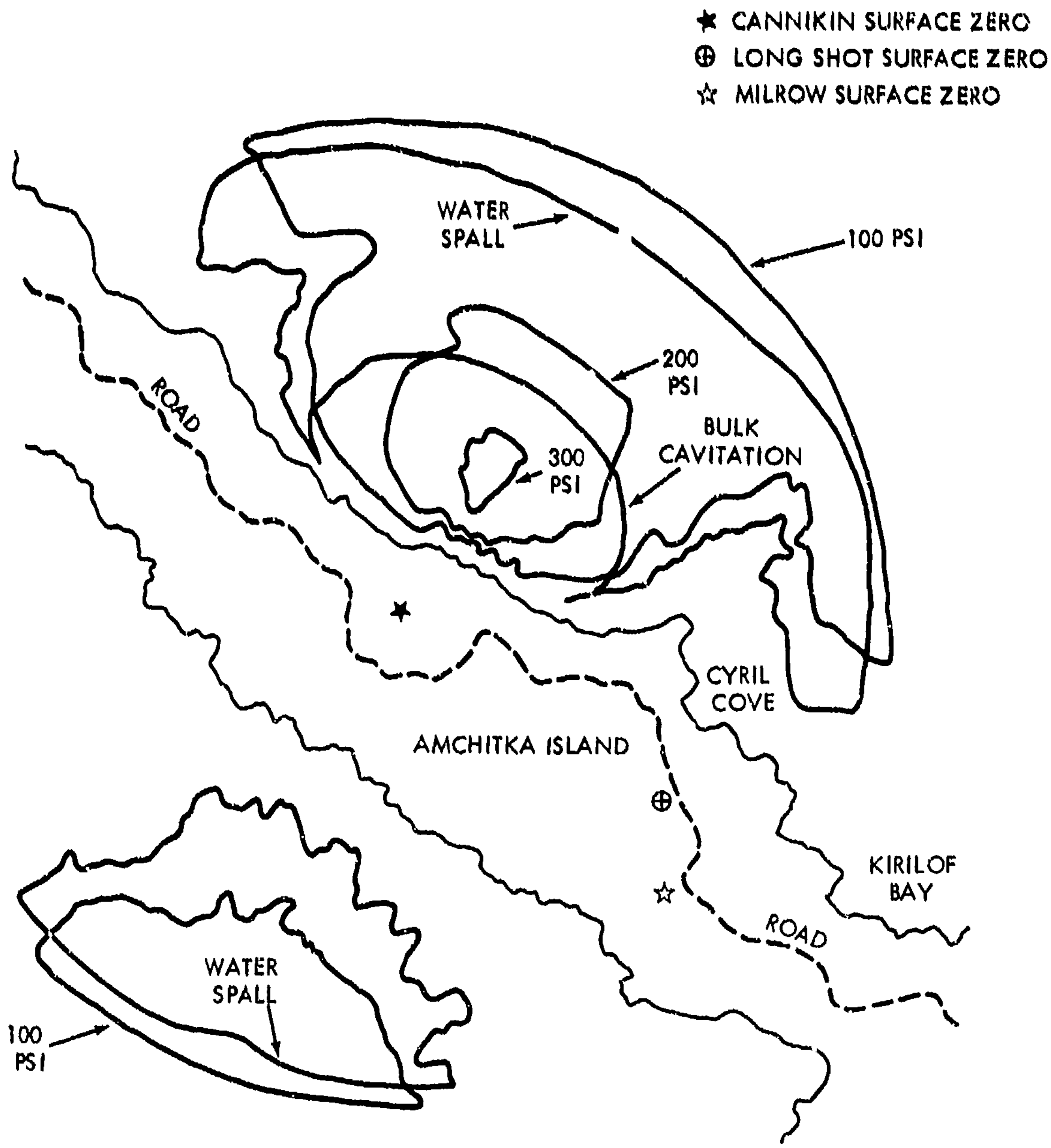

FIG. 7 MAP SHOWING CONTOURS OF CANNIKIN BOTTOM PRESSURES, LIMIT OF WATER SPALL, AND LIMIT OF BULK CAVITATION.

BIOLOGICAL EFFECTS OF UNDERGROUND NUCLEAR TESTING ON MARINE ORGANISMS. I. REVIEW OF DOCUMENTED SHOCK EFFECTS, DISCUSSION OF MECHANISMS OF DAMAGE, AND PREDICTIONS OF AMCHITKA TEST EFFECTS*

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Merritt (1972, 1973, and this Conference) has described the characteristics of the waterborne shock waves created by the Milrow and Cannikin underground nuclear detonations. The following introduces a portion of the investigations conducted to relate the effects of these perturbations upon organisms in the marine environment adjacent to the Amchitka Island test site. Since 1967, as a component of the US AEC's Bioenvironmental Safety Program on Amchitka, coordinated by Battelle Memorial Institute's Columbus Laboratories, the University of Washington's Fisheries Research Institute (FRI) has performed task-specific studies concerning the effects of the nuclear testing on the area's marine fish, invertebrate, and algal communities. This discussion presents (1) the level of our understanding of nuclear-induced or similar shock wave effects upon fish, (2) the potential mechanisms of damage applicable to the Amchitka situation, (3) the resulting prediction of effects formulated preparatory to the Cannikin test, and (4) our experimental approach to documenting the actual effects of the test. John Isakson (this Conference) continues this discussion with the empirical results of our experiments, observations, and studies and will summarize the effects of the Milrow and Cannikin tests on marine organisms as assessed by FRI and some of the other biological investigators.

An underground nuclear detonation-induced shock wave can produce a variety of biological effects on the adjacent marine environment. It may directly inflict physical damage on coastal marine organisms by stressing their body tissues, organs, and contained air spaces either mechanically or through the effect of pressure differential. It may also alter the habitat, especially in the ecologically sensitive intertidal zone, and thereby indirectly produce distinct changes in species composition, distribution and/or abundance.

Localized habitat disruption associated with nuclear tests on Amchitka previous to Cannikin has been well documented (Seymour and Nakatani, 1967; Kirkwood, 1970; and Merritt, 1970). The biological effect on bottom organisms caused by the movement of the sea floor may be significant, but little definitive documentation existed. The correlation between measured shock wave hydrostatic parameters and observed biological effects had not been adequately established for shock conditions similar to the Amchitka situation. Thus, the characteristics of waterborne shock waves specific to biological damage were assessed through the literature in order to better predict the Cannikin effects and to design the experiments to test those predictions. This survey revealed comparable effects on fish originating from three sources exclusive of nuclear tests: (1) underwater explosions, (2) earthquakes, and (3) specific problem-oriented laboratory experiments.

* Supported by the U. S. Atomic Energy Commission Contract AT(26-1)-171 through subcontract from Battelle Memorial Institute, Columbus, Ohio.

Previous relevant investigations into the effects of underwater explosions on fish and other marine life have occurred in conjunction with naval ordnance tests in Chesapeake Bay (Bennett, 1947; U. S. Navy, 1947; Chesapeake Biological Laboratory, 1948; and Coker and Hollis, 1950), seismic oil exploration in the Gulf of Mexico (Gowanloch and McDougall, 1945 and 1946), Lake Erie (Ferguson, 1961), in California (Alpin, 1947 and 1962; Baldwin, 1954; Fitch and Young, 1948; Fry and Cox, 1953; Hubbs and Rechnitzer, 1952; and Hubbs et al., 1960), Oregon-Washington (Oregon Fish Commission, 1962; and Rulifson and Schoning, 1963) and British Columbia coastal waters (Kearns and Boyd, 1965) and in Alaska (Bright, 1957; Alaska Department of Fish & Game, 1959; and Roguski and Nagata, 1970) and concerning marine engineering activities such as the removal of Ripple Rock from Seymour Narrows in British Columbia (Thompson, 1958). Dr. Young (Young, 1973) has recently summarized, in part, the results of these investigations. Related experiments have also been performed in Philippine (Thiemmedh, 1949; and Ronquillo, 1950 and 1953) and Japanese coastal waters (Koyama, 1954; and Kuroki and Kumanda, 1961) and in the Soviet Union (Tsvetkov et al., 1972; and Drabkina and Vodovozova, 1973). Natural shock waves induced by earthquakes have also been known to produce fish mortalities (Kachadoorian, 1965; and Kirkwood and Yancey, 1965) as was observed in the 1964 Alaska earthquakes. In an analogous situation, shock wave induced or related fish mortalities have also been examined in association with the passage of fishes through dam siphons (Hogan, 1941), pumps (Foye and Scott, 1965), or hydroelectric power turbines (Muir, 1950; Rowley, 1955; Holmes and Donaldson, 1961; Cramer and Oligher, 1964; and Sutherland, 1972).

Two mechanisms of biological damage applicable to fish were indicated in these studies; (1) changes in pressure over (overpressure) and under (underpressure) ambient hydrostatic pressures, and (2) bulk cavitation. High explosives detonated under water were shown to create instantaneous pressure changes which were especially injurious to classes of fish possessing air bladders. While many investigations correlated the rapid rising (i.e., 1-2 msec) peak pressure components of the shock with observed fish mortality or damage, a number of the more refined studies, such as the two conducted by Dr. Carl Hubbs and his associates (1952 and 1960), suggested that the negative pressure phases accompanying such high explosive shock waves (see Cole, 1948) were responsible for the more deleterious mechanisms of damage to fish. Other, slower burning explosive shock waves (i.e., risetimes of 6-7 msec) which produced up to four times the peak overpressures as high explosive waves but which did not produce underpressures or decompression pulses, were essentially non-injurious.

Risetimes for nuclear-induced shock waves traveling through rock (Merritt, 1973a and this Conference) are exceedingly longer than in explosion produced waves, e.g., in the order of 70-100 msec for the Milrow test (Merritt, 1971). So, even if rapidly rising overpressure is a factor in explosion produced fish mortalities, it appears not to be the dominant factor in the case of nuclear-induced shock waves. Nuclear shock waves do, however, most commonly have a component of negative pressure in their wave form. Figure 1 illustrates the differences between the three types of documented shock waves--high explosive induced waves (50-1,000 cycles), slower burning black powder-produced waves (140-170 cycles), and low frequency nuclear-induced waves (10-15 cycles). Earthquakes produce shock waves in the order of 15-25 cycles.

While fish can apparently tolerate compression pulses of high amplitudes with risetimes longer than 1-2 msec, the longer a decompression phase persists, the more

detrimental its effects. Thus, the first specific mechanism of potential damage from a nuclear-induced shock wave is associated with the negative pressures produced in the refraction cycle (Wentzell et al., 1969; Merritt, 1973a & b; and this Conference) of the shock wave as experienced by an organism positioned in the water column. As noted in the majority of literature-documented fish kills, the anatomical morphology, i.e., whether or not the fish has an air bladder[1] and the form of the bladder, determines the scale of shock wave effect on the organism. Fishes without air bladders, predominantly those species living along the shore, in deep water or associated with the bottom (Brown, 1957; Jones, 1951, 1952, and 1957; and Jones and Marshall, 1953), are least susceptible to mechanical decompression damage. Lacking this sack of gas these fishes apparently do not suffer from the effects of the gas expansion during the passage of the decompression phase of a shock wave. Fish with an air bladder are of two forms--"physostomus," those possessing an open duct connecting the air bladder to the alimentary canal (Figure 2), usually at the pharynx; and "physoclistous," those forms without the pneumatic duct. Physostomus forms are prevalent among the pelagic surface dwelling fishes and the physoclistous forms among those inhabiting the midwater environment.

Although physostomus fishes are able to expel air bladder gas rapidly through the pneumatic duct, the volume of the air bladder generally cannot be manipulated rapidly (Sundnes and Bratland, 1972); although, there are indications that in some physoclists muscular tensions around the bladder can provide short-term volume regulation (Sundnes and Gytre, 1972). While the physoclistous fishes suffer potential rupture of the air bladder wall with significant decompression, the physostomus fishes will be less likely to suffer rupture as long as the passage of gas out through the pneumatic duct is at a volumetric rate higher than the expansion of that volume of gas still within the bladder. It is unknown whether or not this is possible over the potential decompression phase of a nuclear-induced shock wave. Both forms, however, are capable of losing buoyancy under minimum decompression conditions and it has been suggested that a 1% change in buoyancy is sufficient to disable a fish (Jones, 1952).

The decompression effect upon a fish with an air bladder will be a function primarily of: (1) the form of air bladder, (2) the tensile strength of the air bladder wall, (3) the resistance that the body wall and internal organs offer to the expansion of the bladder gas, and (4) the percentage volume of the air bladder gas relative to the ambient pressure. Generally, it has been suggested that in physoclistous fishes, a 3/5 reduction in relative pressure will be sufficient to rupture the air bladder wall (Jones, 1951 and 1952). Decompressions of from 14 to 50 psi have been documented to be lethal to physostomus fishes (Bishai, 1961a & b; Hogan, 1941; and Muir, 1959) and, theoretically, even lower values will apply to physoclists. Such threshold values should be considered in the light of the ambient pressures (position in the water column) in all cases. For, while the percentage volume expansion of the air bladder gas decreases with depth and the bladder at depth is thus more tolerant of expansion during decompression, the threshold underpressure value triggering cavitation (and thus limiting the potential underpressure) increases with depth and thus at depth the fish is subjected to a mechanically more intense underpressure stress than in a shallower situation.

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[1] The air bladder is a highly vascular, usually single-chambered, hollow, gas-filled organ located immediately below and along the length of the vertebral column between the alimentary canal and kidneys.

To this point discussion has considered only the potential effects of the mechanical expansion of air bladder gas during decompression. The second potential mechanism relates to the phenomenon of bulk cavitation discussed by Cole (1948), Ackerman (1953), Cushing (1961 and 1969), Cushing et al (1962), Walker (1966), Waldo (1969), Wentzell et al (1969), Snay (1970), Gaspin and Price (1972), and Merritt (1973 and this Conference). At a threshold level, assumed to be absolute 0 pressure, gas bubbles expand to collapse with the extraction of energy from the source of decompression. It is becoming more apparent that cavitation of an organism's body fluids, those that contain gases, is also a potential mechanism of physiological damage under the correct circumstances. It has been theorized to be a factor in documented explosion-induced fish kills (Hubbs and Rechnitzer, 1952), as a mechanism of medical concussion (Ward et al, 1948) and in the nitrogen supersaturation problem in the Columbia River system (D'Aoust and Smith, in prep.). Two aspects may be involved: (1) the accumulation of gas bubbles, especially nitrogen, in the vascular system of the organism, resulting in embolism, and (2) the expansion of the gas bubbles to the point of inflicting physiological harm upon the blood vessels and organs. There is no experimental data establishing whether or not the decompression phase of a nuclear-induced shock wave is of long enough duration to allow nitrogen or other gas bubbles to accumulate to the point of embolism damage. Theoretically, these gases should be completely redissolved upon initiation of the following compression phase of the shock wave and will not remain in the vascular system. The relatively short period of the decompression may also limit the volume of gas coming out of solution within the fish body fluids. The instantaneous expansion of any such gases, however, within the vascular system and organs may be carried to the point of rupturing vessel and organ walls, initiating lesions and hemorrhaging if not initially inflicting fatal damage. Such damage in the circulatory system, gill membranes or certain portions of the central nervous system would be immediately fatal but sublethal damage to the peripheral nervous system or the gas exchange system for the air bladder would also place the fish in a situation of likely predation and eventual indirect mortality. There is no data available, that I know of, biologically documenting this mechanism and the need for a comprehensive experiment is essential if we are to determine whether or not it is a real factor of shock wave phenomenon as related to biological injury.

Two little understood phenomenon of hemolymph changes in insects (Newcombe, 1966) and leukocytic composition of fish blood (Drabkina and Vodovozova, 1973), have also been linked to shock wave pressure changes but the mechanism is not well established and may not be applicable.

This is the point of information at which FRI stood preparatory to the Cannikin test. The results from the Long Shot and Milrow tests were inconclusive and sometimes ambiguous in the light of this knowledge. The only predictive experiments conducted preparatory to the Milrow test, involving mechanical compression if the sea otter, Enhydra lutra, and a few fish species (Wright, 1968), disregarded underpressure. Milrow test-time effects experiments (Kirkwood, 1970; and Merritt, 1970) lacked the comprehensiveness (i.e., no air-bladdered fish were utilized) to project the results to Cannikin. Thus, with the aid of Dr. Merritt and the Sandia Laboratories, we used the Milrow physical shock wave data and theoretical pressure functions to produce a map of the over- and underpressure regime as predicted for the marine environment adjacent to the Amchitka Cannikin test site (Figures 3 and 4). With a conceptualization of the distribution of peak pressures and limits of cavitation we superimposed this on our accumulated knowledge of the nearshore and offshore fish communities, their constituents (see Isakson et al, 1971 for description) and their known or suspected susceptibility to shock waves.

Using this procedure, we predicted that sizable numbers of the endemic physoclistous forms, the Pacific cod, walleye pollock, and rockfish species, would probably be killed in the offshore ($\geq$ 36 m) waters within the portion of that region subjected to high underpressure and cavitation (Kirkwood and Fuller, 1971). With the combined effect of underpressure cutoff by cavitation, surface spall and the predominantly physostomus forms of fish (mostly salmonids), the pelagic surface community was considered to be less vulnerable and potentially unaffected. The midwater fishes, about which we know the least, were potentially susceptible to lethal pressure changes in the case of the physoclists, but no quantitative predictions were possible. The bottom fishes, usually lacking an air bladder, were assumed to be least susceptible to shock wave mortalities. The two nearshore communities were considered similarly but in the light of higher overpressure and lower underpressure values than further offshore. The nearshore physoclists, the Pacific cod and dusky rockfish, were considered to be in moderate danger of fatal shock wave pressures if attenuation within submarine canyons or other possible mechanisms of focusing underpressure should occur. Physostomus and non-air bladdered fishes were not predicted to be fatally inflicted. The prediction summarized by saying that, considering the relatively low percentage of Amchitka's fish communities involved, the reduction of its fish populations would not be irreversible and might, in fact, be undetectable.

With predictions in hand we then designed an experiment to test them. A system of live-cage strings (Figure 5) designed to hold fishes at the surface, bottom, and at midwater were built to be set at varying distances from the test site in positions to maximize the spectrum of peak pressure changes (Figure 6). Fishes representative of the different communities were collected, tagged and were to be placed in their respective live-cages in the water column. Each cage was to be instrumented by Sandia Laboratory using passive gauges recording peak over- and underpressures. Unfortunately, recording active gauges which were used during the Milrow test documentation could not be used for various reasons. But the assumption that wave forms would be similar and could be extrapolated from the peak pressure values and land-based acceleration data is probably valid. This system of live-cages with the experimental animals was to be set in place the night prior to the Cannikin detonation but due to winds gusting over 80 knots pushing 30 ft seas the live-cage strings could not be set as planned and the test schedule proceeded without this documentation. Mr. Isakson will continue the discussion of Cannikin effects in this light.

In summary, the potential mechanisms of biological damage to fish resulting from a nuclear-induced shock wave appear to involve (1) mechanical damage from bottom acceleration and rockspall, (2) the synergistic effect of compression to decompression producing the mechanical expansion of gas spaces within the organism, (3) effects of cavitation, and (4) possibly the alteration of blood constituents. The indirect effects of the shock wave should also be considered in a truly ecological approach. Loss of fish or other marine organisms may reduce food resources for other species and place an unusual stress upon the community's food web and increased predation created by the influx of a formerly minor constituent may also be a real consideration. The determinants of biological damage, as concluded from our studies involve the (1) anatomical morphology, and (2) ecological characteristics of the various members of the fish community, and (3) the physical characteristics of the environment as produced by the introduced shock wave.

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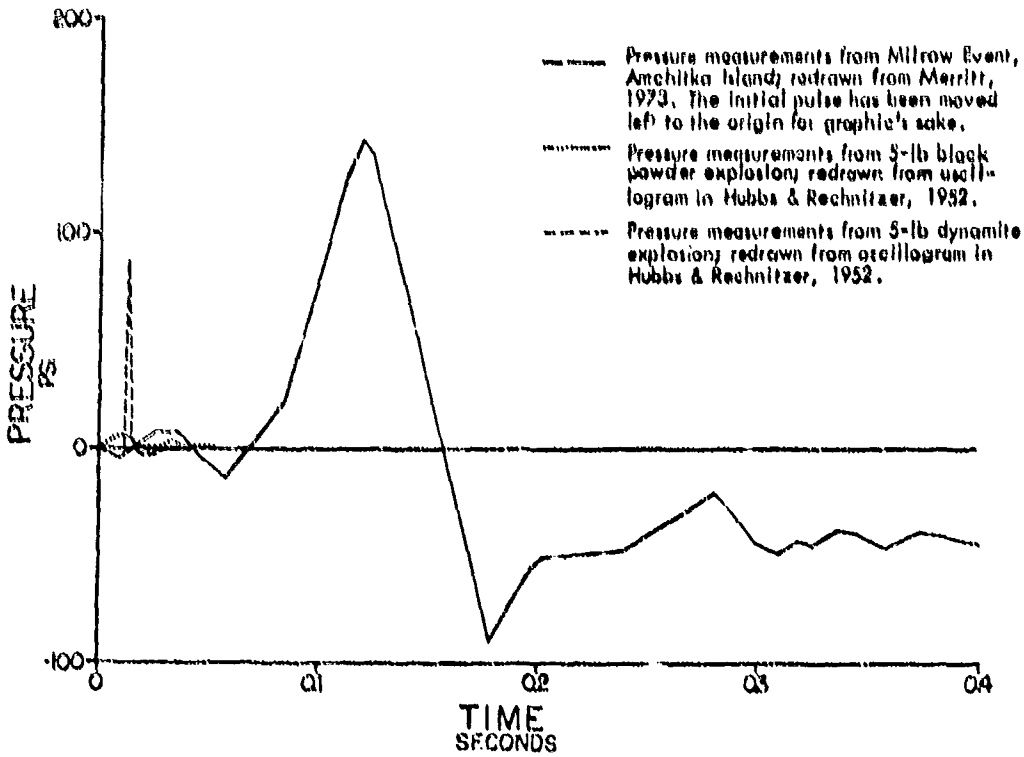

FIG. 1 PRESSURE DISTRIBUTION AND WAVE FORMS FROM MILROW EVENT, BLACK POWDER AND DYNAMITE EXPLOSIONS.

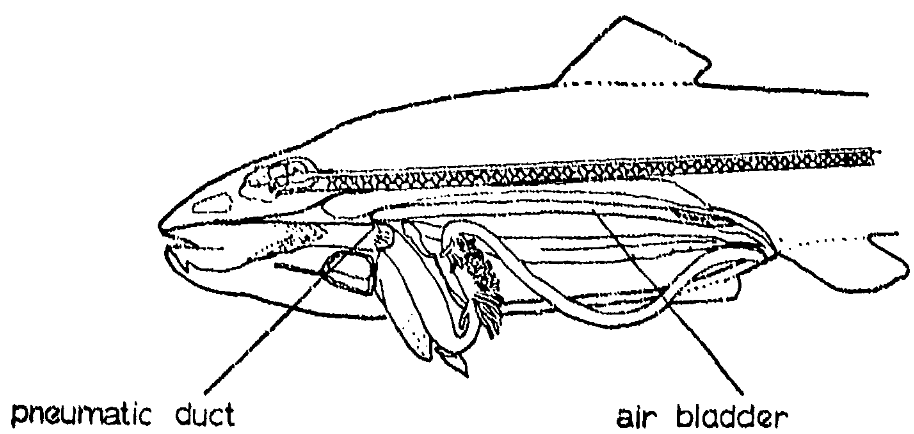

FIG. 2 DIAGRAMATIC ILLUSTRATION OF PHYSOSTOMUS FISH, SALMO FARIO; PHYSOCLISTOUS FISHES LACK THE PNEUMATIC DUCT CONNECTION BETWEEN THE AIR BLADDER AND THE ESOPHAGUS. REDRAWN FROM: HARMER, S.F. & A.E. SHIPLEY (ED.) 1904. CAMBRIDGE NATURAL HISTORY, VOL VII. HEMICHORDATA, ASCIDIANS AND AMPHIOXUS, FISHES. MACMILLAN & CO., LONDON.P.255.

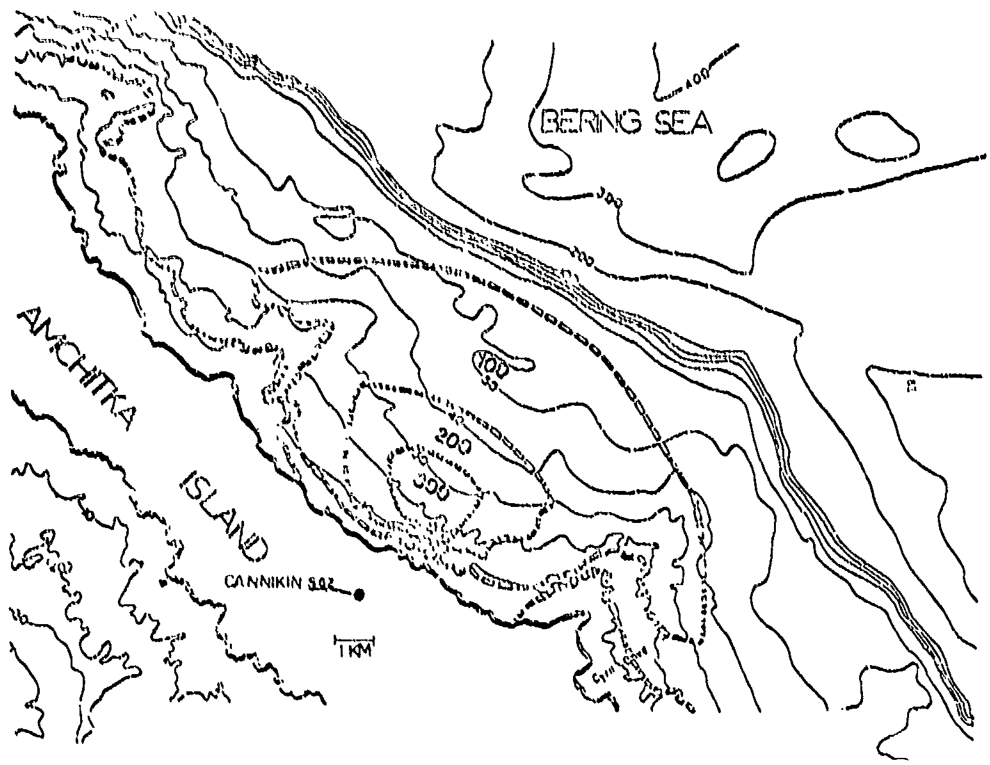

FIG. 3 PREDICTED OVERPRESSURE IN POUNDS PER SQUARE INCH AT BOTTOM IN BERING SEA ADJACENT TO CANNIKIN SGZ.

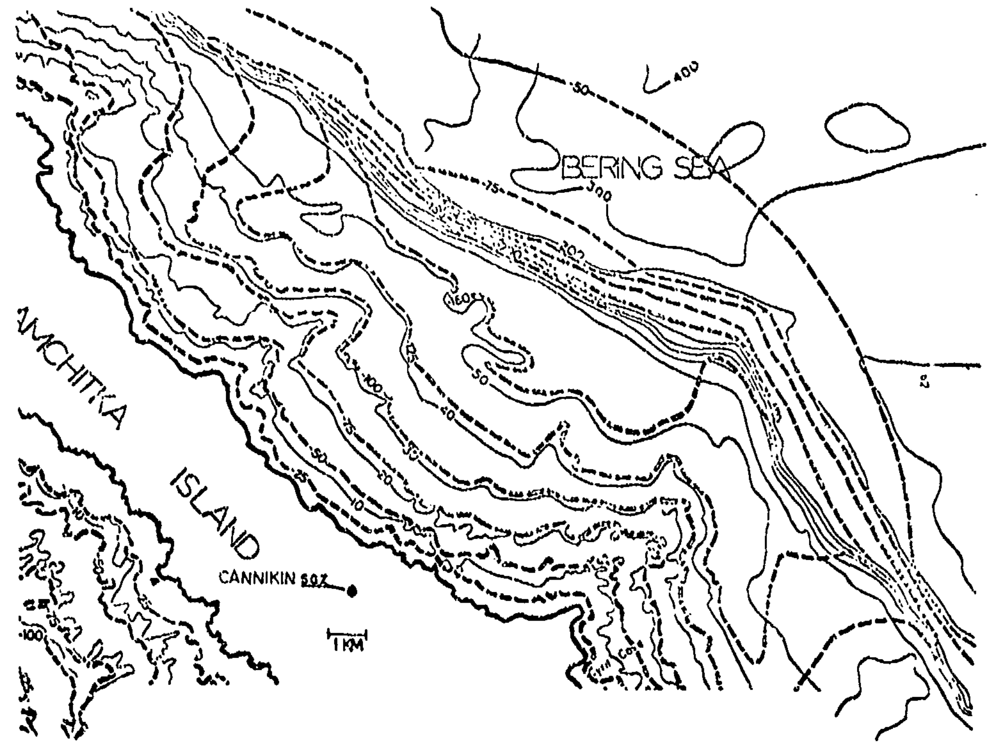

FIG. 4 PREDICTED UNDERPRESSURE VALUES IN (-) POUNDS PER SQUARE INCH AT THE BOTTOM IN BERING SEA ADJACENT TO CANNIKIN SGZ.

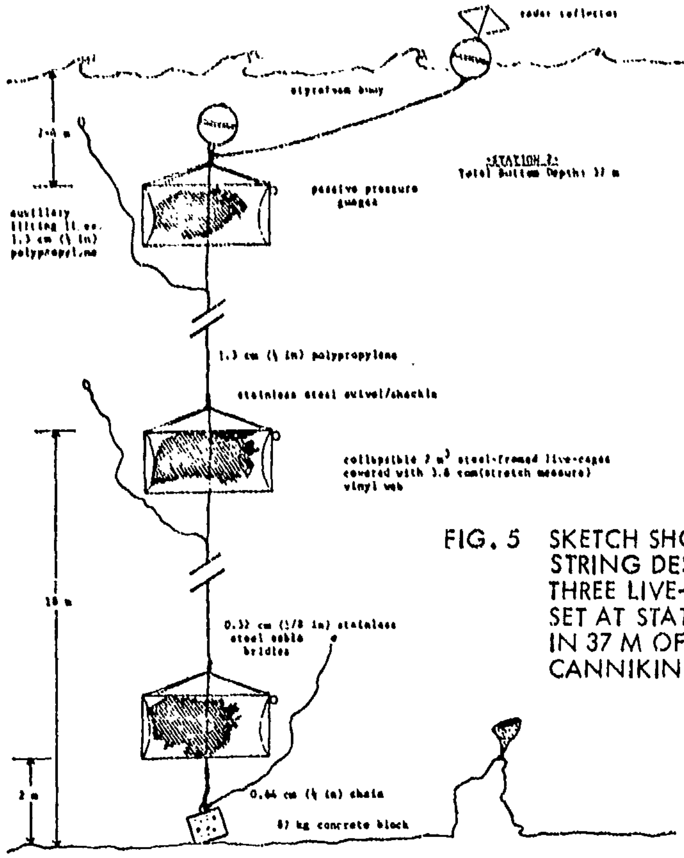

FIG. 5 SKETCH SHOWING LIVE-CAGE STRING DESIGN; EXAMPLE IS THREE LIVE-CAGE STRING TO BE SET AT STATION #2 (FIGURE 6) IN 37 M OF WATER OFFSHORE CANNIKIN SITE.

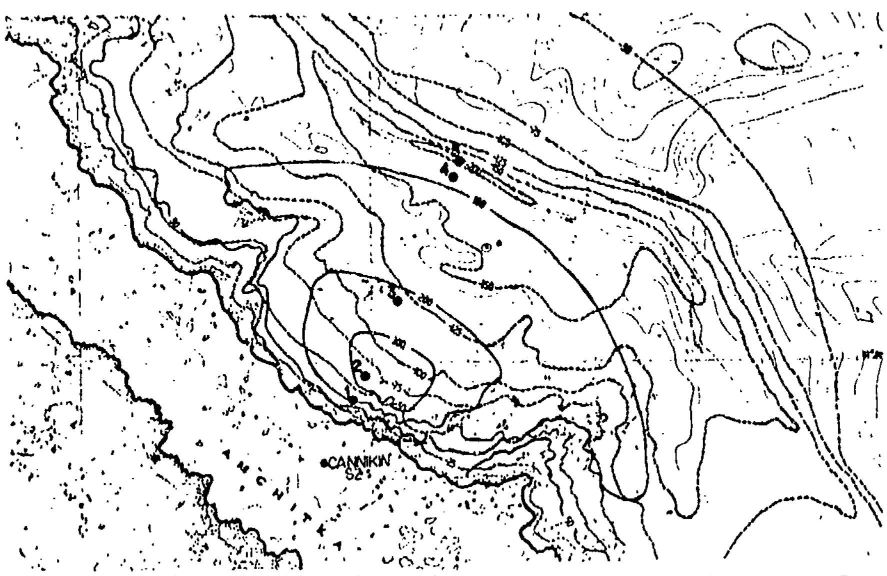

FIG. 6 LOCATIONS OF FIVE LIVE-CAGE STRINGS DESIGNED TO BE LOCATED AT VARYING DISTANCES OFFSHORE THE CANNIKIN TEST SITE ON AMCHITKA ISLAND, ALASKA. REPRESENTATIVE FISHES PLACED AT THEIR RESPECTIVE CAGE LEVELS IN THE WATER COLUMN WOULD EXPERIENCE A WIDE RANGE OF OVER-AND UNDERPRESSURES, SOME ACCOMPANIED BY BULK CAVITATION.

BIOLOGICAL EFFECTS OF UNDERGROUND NUCLEAR TESTING ON MARINE ORGANISMS

II. OBSERVED EFFECTS OF AMCHITKA ISLAND, ALASKA, TESTS ON MARINE FAUNA*

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INTRODUCTION

The Fisheries Research Institute (FRI) of the University of Washington under contract to Battelle Memorial Institute, Columbus Laboratories (BCL) (in turn under contract with the U.S. Atomic Energy Commission's Nevada Operations Office) began studies in 1967 to predict and evaluate the effects of two proposed underground nuclear tests at Amchitka Island, Alaska (later named Milrow - October 1969 and Cannikin - November 1971). BCL coordinated the overall Amchitka Bioenvironmental Safety Program.

Readers are asked to review the quoted references for specific details beyond the scope of this paper.

The physical characteristics of the water-borne shock waves produced by underground nuclear tests were discussed by Merritt, 1973 (SC-RR-72-0547) and this Conference. A review of the literature as related to our work on the biological effects of these shock waves was discussed by Simenstad (this Conference). This paper will present the observed biological effects of underground nuclear tests both from the literature and from direct observations for the Longshot, Milrow, and Cannikin underground nuclear tests at Amchitka.

LONGSHOT

The biological effects of the October, 1965 Longshot test on the Amchitka marine environment were reported by Seymour and Nakatani, 1967 (RL-1385-1). This was an 80-kt device buried 700 m (2,300 ft) underground. These authors reported no rock greenling (*Hexagrammos lagocephalus*), and no red Irish lord (*Hemilepidotus hemilepidotus*) (of 52 total fish) were killed in live boxes as close as 2 km to SZ (surface zero). Amphipod predation limited the evaluation of results, as more desirable species having air bladders such as salmon were killed prior to the test. The only dead or injured animals found were two Pacific cod (*Gadus macrocephalus*) and three diving birds found 2 hours after the test. Counts of sea otters indicated no damage to their population at Amchitka.

MILROW

The biological effects of the Milrow test of about 1 megaton and buried 1.2 km (4,000 ft) in October 1969 are well summarized by Kirkwood, 1970 (BMI-171-126), Merritt, 1970 (NVO 79), and Burgner *et al.*, 1971 (BMI-171-137).

* Supported by the U.S. Atomic Energy Commission Contract AT(26-1)-171 through subcontract from Battelle Memorial Institute, Columbus, Ohio

Fish

In the fish study, FRI had sampled the offshore fishes with a chartered commercial trawler and nearshore fishes by small boats prior to Milrow beginning in 1967. Various nets, trawls, and longlines were utilized. Numerous fish were retained alive and held for use in live box experiments similar to those for Longshot. Again, the effort was plagued by amphipod predation. By test time we were again left with the hardier species (rock greenling and red Irish lords) used at Longshot. Both lack air bladders as indicated previously. More desirable species were eliminated by pre-test experiments which indicated poor survival in holding pens. Gill net and trawl-captured species were also injured in capture to affect short-term survival. Ocean perch (Sebastes alutus), a rockfish, walleye pollock (Theragra chalcogramma), rock sole (Lepidopsetta bilineata), Pacific salmon (Oncorhynchus), and Pacific cod were so excluded.

Three pairs of live boxes were placed in Duck Cove. These pens were located 2.6 km (8,550 ft), 3 km (9,900 ft), and 4 km (13,000 ft) from SZ on the bottom at depths of 15 m (50 ft), 26 m (84 ft), and 27 m (90 ft), respectively. Sandia personnel reported overpressure levels in these 3 pens as approximately 75 psi, 150 psi, and 130 psi, respectively. A seventh live box was placed 8.6 km (5.5 miles) offshore. This contained four lithodid crabs, a close relative of the king crab. This bottom pen sustained an overpressure of about 40 psi.

The pens were all recovered on the day of the test, and short of a few escapees, all fish and crabs were alive and showed no evidence of injury. The recovered specimens were held in holding tanks for four weeks and at the time of release appeared to be in similar condition to those control fishes held for the duration in the Constantine Harbor live pens.

Comparisons of pre- and post-test catches of fishes indicated no detectable changes in trawl or gill net catches. Direct observations located three unidentified dead fish, but these could not be recovered from the air and were not located in follow-up beach surveys.

FRI was left with little evidence of the impact of Milrow on marine fishes. In contrast, investigators from Utah State University located numerous dead three spine stickleback (Gasterosteus aculeatus) in nearby freshwater tundra ponds. These fish were autopsied and exhibited ruptured air bladders, internal hemorrhaging and pale gills and gill arches (Kirkwood, 1970).

Marine Mammals and Birds

Other investigators (Kirkwood, 1970) conducted surface live box experiments involving sea otters in a beach located pen in Duck Cove some 1.3 km (4,300 ft) from SZ. Additionally two floating pens were located 2.8 km (9,200 ft) and 3.1 km (10,200 ft) from SZ. A third pen was not used. All pens experienced no overpressures as determined by Sandia personnel (Merritt, 1970).

Observations post-event indicated two otters were missing from the closest floating pen and one other otter in the pen was dead. A necropsy indicated no test-related cause for the death. Nothing observed gave any indication of the actual cause of death. The remaining otters were held in the Constantine Harbor holding pens for 4 to 10 days before release, except for four animals that were sacrificed and necropsied three days after the Milrow test. No detectable damage was noted (Kirkwood, 1970).

Otter surveys later indicated no decline in their numbers that could be attributable to the Milrow test. A dead porpoise was found three days after the test. Autopsy indicated a fractured rib that had penetrated the lung causing death. There was no tissue damage of the type that would be expected from excessive overpressure (Kirkwood, 1970).

Censuses of birds indicated 28 common species were seen both before and after the Milrow test. Two less common species (a crested auklet and a fulmar) were seen only before Milrow while two other species (black-headed gull and horned grebe) were seen only after the test. This was not construed as a test effect. Aviafauna surveys showed no changes in population sizes attributable to Milrow (Kirkwood, 1970).

CANNIKIN

The biological effects of the November 1971 Cannikin test, of less than 5 megatons and buried 1.8 km (5,875 ft), are summarized by Kirkwood and Fuller, 1972 (BMI-171-147), and Nakatani et al, 1973 (BMI-171-150).

Similar to the Milrow effort, exploratory fishing was carried out by a chartered trawl vessel offshore and by larger small boats nearshore in areas on the Bering Sea side of SZ both before and after the Cannikin test. The live box plan was very elaborate as Mr. Simenstad (this Conference) indicated. Unfortunately, we were stopped by 80+ knot winds which made the sea too rough for live box placement. One live box string of two pens was placed in Constantine Harbor prior to the MV Commander's departure for a test time holding station. The bottom pen was 17 m (54 ft) deep and the surface pen was 2 m (10 ft) deep. The lower pen contained rock greenling, Pacific cod, Pacific halibut (*Hippoglossus stenolepis*), red Irish lord, a rock sole (*Lepidopsetta bilineata*), a great sculpin (*Myxocephalus polyacanthocephalus*), and a dusky rockfish (*Sebastes ciliatus*). The upper pen contained rock greenling and Pacific cod.

On recovery 3 hours after the test, only one Pacific cod in the upper box exhibited an equilibrium problem. Because other individuals of the same species had no observable problems and because this site was about 15 km (9.3 miles) from SZ, this was thought the result of handling and not a test effect.

Sea conditions and nightfall limited aerial observations by helicopter on the day of the test. A field party made a brief beach survey on the Bering Sea side of Cannikin SZ about 4 hours after the test. Fish were found then as well as throughout an intensive survey period from one to three days after the test. Intermittent surveys continued for about 14 days. Surveys were concentrated on both coastlines as related to the predicted water pressure regimes presented by Merritt (1973).

The survey results for the marine fishes recovered is shown in Figure 1. The dashed-line indicates those areas walked by various survey teams. The numbers and dates of recovery are noted by species. Wind direction was approximately to the East and was of moderate velocity. Currents on the Bering Sea side are generally to the SE. These are felt to be important variables in the evaluation of these recovered fishes. Pacific Ocean recoveries indicate fish kills of air bladdered species (Pacific cod and rockfish) not seen on the Bering Sea coast where a larger water pressure regime was predicted. Beach survey results would indicate

these species killed on the Bering coastline were probably driven offshore and longshore assuming that they floated. The bulk of the fish (277 rock greenling) were located in an area where the intertidal bench was lifted as much as 1 m (3.3 ft). Many of these rock greenling were stranded there as the test was conducted during a high tide when this species makes feeding excursions above the flooded intertidal bench. Other individuals were washed up on beaches and not obviously stranded. Pacific sandfish (Trichodon trichodon) were obviously stranded in the intertidal beach area they were dug into at test time.

Autopsies were carried out on some of the rock greenling by Dr. Robert Rausch of the US Public Health Service Laboratory at College, Alaska. With the time required in his autopsies of marine mammals and birds only 23 rock greenling were autopsied. Of these, about half exhibited no evident injury and are thought to have been those that were stranded out of water by the uplifted bench. The remaining rock greenling exhibited hemorrhaging in the brain cavity and/or the viscera. These fishes are thought to be those that did not appear stranded and were killed either by direct contact with the bottom (as they habitually lie on the bottom) or by water pressure changes severe enough to cause such internal damage.

Secondary indications of rock greenling injury were seen in shallow adjacent waters in which trammel net catch per unit of effort declined three-fold but began to recover to near pre-test levels about 15 days after the test when weather prevented further sampling (Figure 2). By the following fall, catches were back to normal except in this ineffective sampling period when kelp beds were very dense and difficult to fish in. Adjustments of the nets leadline brought catches up, indicating that the greenling population had recovered in this area at least by August 1972. Recovery was by immigration from adjacent and unaffected areas.

Additionally, offshore bottom trawling revealed a significant reduction in the catch of rock sole, a flat fish lacking an air bladder. This species underwent a decline in catches which averaged 150 rock sole per hour pre-test and went to 22 rock sole per hour post-test. Other bottom species (i.e., Pacific halibut and Pacific cod) were too variable within treatments to indicate differences with analysis of variance between treatments. Rock fishes and cod did disappear from post event survey echo traces over untrawlable bottom areas, such as submarine pinnacles and ridges. Offshore sampling this past fall a year after Cannikin revealed a recovery of rock sole to pre-test levels off Kiriloff Bay and in the Bering Sea area immediately adjacent to Cannikin SZ. Rock sole recovery was by immigration from adjacent unaffected [illegible]

An interesting occurrence occu[illegible] three [illegible] after the test when a rockfish was captured dead in a trawl haul in the Bering Sea adjacent to Cannikin SZ. The fish was badly decomposed, but does indicate that not all air bladdered fish do float. This catch yields some additional evidence beyond echo sounding of fish kills in untrawlable areas that this species normally inhabits while alive.

Our conclusions on the nearshore and offshore fish kills from Cannikin were:

(1) The test produced localized kills on both Bering and Pacific sides of the test site with prevailing winds and currents distributing them as shown in our beach survey.

(2) Original estimates of thousands of nearshore and offshore fish killed (Kirkwood and Fuller, 1972) does not seem out of line with the data at hand, if a kill estimate has to be made.

(3) The numbers killed are not significant in light of the fact that the habitat was not so greatly affected to influence carrying capacities in any significant way as noted by the recovery of rock greenling and rock sole from adjacent, unaffected areas.

(4) The only way testing could have a significant impact on Amchitka's marine fishes is if tests were continued (as they are not planned to be), to cause a cumulative impact on fish species sensitive to the water-pressure changes generated in adjacent marine areas by underground nuclear tests (i.e., each test would reduce the capabilities of recovering by immigration from unaffected areas).

(5) Documented experiments indicating greater sensitivity to air bladdered fish species must also consider the position of other fish species (near bottom or over flooded intertidal benches) before automatically eliminating such species from possible damage from underground nuclear tests on an island such as Amchitka. Recovery of rockfish and cod skeletons, and the disappearance of these species from echosounder traces also indicates these species having air bladders were also affected by the Cannikin test.

Marine Mammals and Birds

The effects of Cannikin on marine mammals were ascertained by pre- and post-test surveys of the island's population and beach surveys after the test. Early reported sea otter kills of 900-1,100 animals (New York Times, December 11) were later revised. Without getting into all the details of these surveys and analyses I will quote portions of the summary of Estes and Smith (1973) as follows:

> "13. The sea otter population of Amchitka Island is estimated to number between 6,325 and 7,501 animals."
>
> "19. A population decrease of about 60 percent was observed in Area A between June 1971 and June 1972." [Author's note: Area A, encompasses about 9 miles (straight line measurement) of Bering Sea coastline adjacent to the Cannikin test site, and 1,205 sea otters were observed there on June 6, 1971.]
>
> "20. Indicated population reductions are believed to have resulted mainly from the Cannikin event. However, movements of animals associated with periods of reproductive activity obscures the interpretation."

I refer the reader to Estes and Smith (1973) for more specific details. Their most important conclusion about sea otter mortality is that the "population will suffer no long-term effects from Cannikin."

Twenty-three dead or injured sea otters were located immediately following the event, of which fifteen suffered damage attributable to physical effects from the Cannikin event (Estes and Smith, 1973). One otter was recovered off the bottom in a trawl 2.5 km (9,000 ft) off shore indicating all killed did not float as was expected. Five dead or injured seals were located after the test (Kirkwood and Fuller, 1972).

The dead birds found after Cannikin numbered 18. Of these one bird, a thick-billed murre, was found to have died of natural causes (Kirkwood and Fuller, 1972).

All recovered otters, seals, and birds were autopsied by Dr. Rausch who has recently completed a report (Rausch, 1973; NVO-130) which summarizes in great detail the physiological findings on marine mammals and birds. The report by Rausch (1973) is abstracted as follows:

> "Animals fatally injured by effects of the Cannikin detonation on Amchitka Island were subjected to post mortem examination, and representative tissues were studied microscopically. From evidence so obtained, in combination with other information, it was concluded that three mechanisms were involved in producing the range of lesions observed: rock-falls; vertical acceleration; and combined effects of over- and underpressures.
>
> Two sea otters, Enhydra lutris (Linnaeus), on the beach at the time of the detonation, were crushed by falling rocks. Eight birds (seven harlequin ducks, Histrionicus histrionicus (Linnaeus), and a pelagic cormorant, Phalacrocorax pelagicus Pallas) also sustained crushing injuries, evidently when exposed rocks upon which they were resting were violently displaced upward by vertical acceleration. Animals that were diving at the time of the detonation were exposed to a pressure-pulse followed by a fall in pressure to cavitation and a subsequent rise to the pre-existing ambient. In ten sea otters and in four harbor seals, lesions produced respectively by overpressure and underpressure were distinguished, although some of the disruptive changes in the lungs could not be specifically related to one of these factors. Fatal injuries in seven birds, representing six species, were attributed to effects of pressure-changes. In two sea otters, traumatic lesions of undetermined origin were superimposed upon those produced by pressure-changes.
>
> Because of the scarcity of injured but still living mammals, it appears that the rate of mortality was high among those that were diving in the critical areas at the time of the detonation, but those at the surface probably were uninjured."

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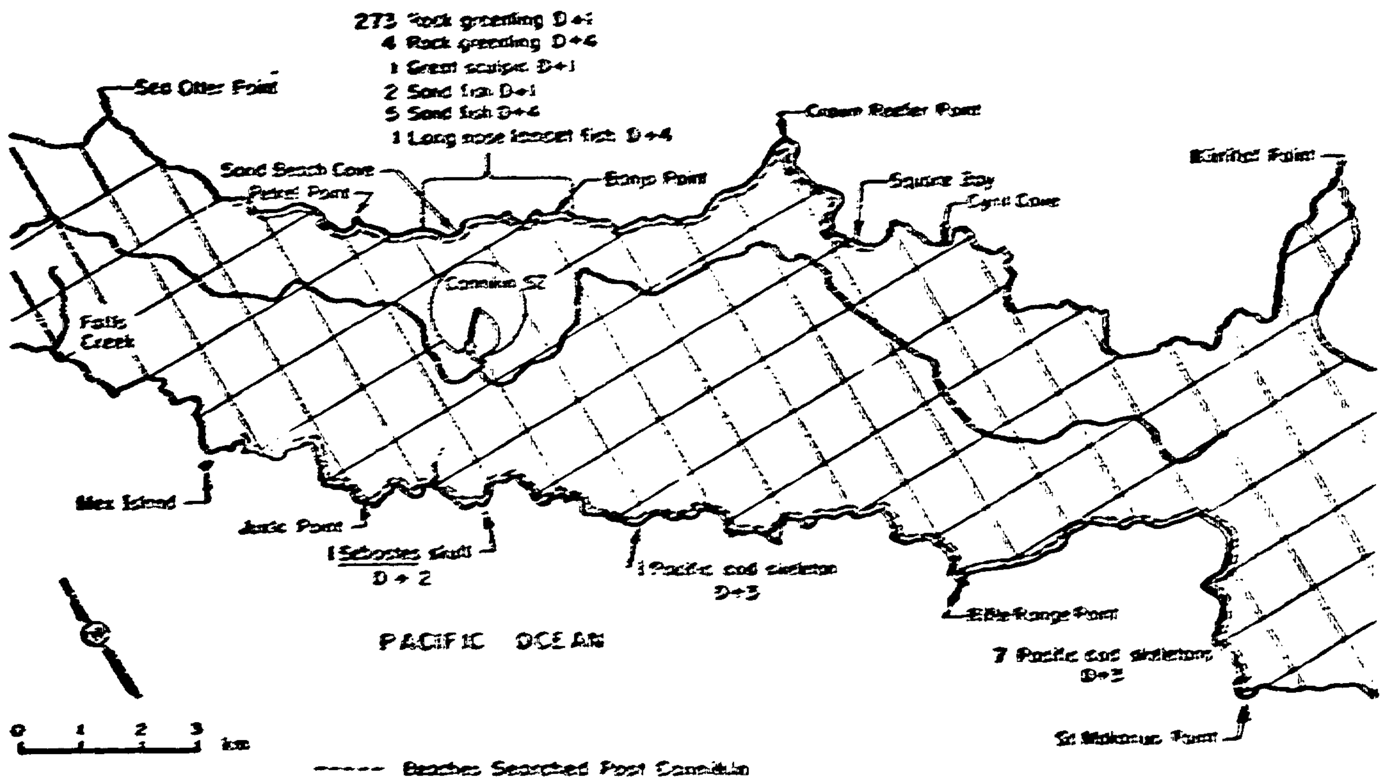

FIG. 1 BEACHES SEARCHED POST-CANNIKIN AND LOCATIONS OF DEAD, INJURED, AND STRANDED FISH AND SKELETONS OF FISH RECOVERED FROM MARINE AREAS POST-CANNIKIN (FROM KIRKWOOD AND FULLER, 1972)

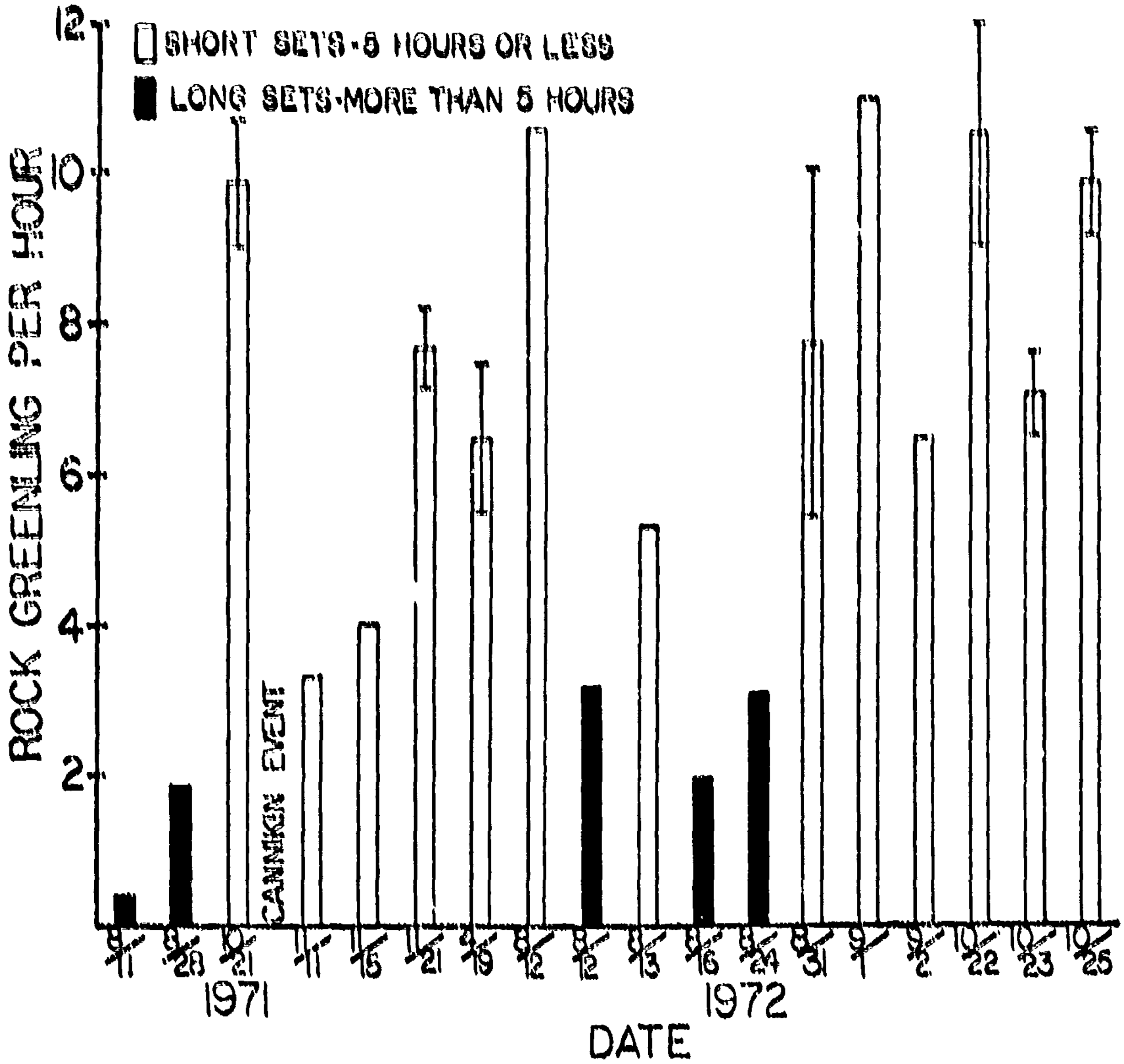

FIG. 2 TRAMMEL NET CATCHES, OF ROCK GREENLING PER HOUR, IN THE NEARSHORE ROCK ALGAE FISH COMMUNITY ADJACENT TO INTERTIDAL SITES IA-2 AND IA-3, AUGUST 1971 THROUGH OCTOBER 1972. A RANGE IS INDICATED FOR TWO SETS ON A GIVEN DAY. SETS WITH CATCH CLUMPED IN ONE OR TWO AREAS OF THE NET'S LEADLINE ARE NOT THOUGHT EFFECTIVE AS THE LEADLINE WAS PARTIALLY HELD OFF THE OCEAN BOTTOM AND ARE SO LABELED. A PERIOD OF DIFFICULT SAMPLING DUE TO DENSE KELP BEDS WAS FROM 8/12/72 THROUGH 9/2/72.

MECHANISMS OF FISH-KILL BY UNDERWATER EXPLOSIONS

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I have recently encountered from several sources the belief that someone, somewhere, fully understands the damage mechanisms and can predict where fish will be killed by underwater explosions. Unfortunately, I do not believe this is true.

We have recently taken a new look at the fish-kill problem, not because the Navy is killing more fish these days, but because we must now be able to estimate the effects of explosive operations on the environment. In terms of numbers of fish killed, explosions always have been, and still are, far less damaging than other offenders such as chemical wastes. Nevertheless, we do need a realistic prediction method for use in preparing and in evaluating environmental impact statements. And that means we need new information because present methods are inadequate for the job.

I will describe here the results of a study[1] that has provided a new prediction approach. The damage model used seems to be plausible, and the lethal ranges it predicts agree reasonably well with the very limited data we have for comparison.

At very short ranges from an underwater explosion all biota will be killed. But one important type of fish, namely, those that have gas-filled swimbladders, are sometimes killed out at much longer ranges than other organisms such as crabs, oysters, lobsters, and even other types of fish that do not have a swimbladder. It happens that the majority of game fish and commercially valuable fish do have gas-filled swimbladders. Consequently, if we can predict the maximum range to which an explosion will harm these fish, we will have made real progress towards predicting the major impact of an explosion on the biological population.

Some of the general characteristics of a typical swimbladder are as follows. First of all, it is a gas-filled sack that is embedded within most bony fish. It is a hydrostatic organ; this is the buoyancy tank that allows the fish to remain weightless in water so that he can hover at any depth without having to expend his energy just to stay afloat. The swimbladder is roughly elliptical, although many different designs are found among the many species of fish that have such organs. The volume of the bladder stays essentially constant. In order to effect the proper density control of the fish, the bladder must occupy about 5% to 7% of the total body volume. The internal pressure must be equal to the external hydrostatic pressure at whatever depth the fish is operating. And in order to maintain this constant volume during pressure variations that are sometimes very great, the swimbladder must have a gas-exchange mechanism of some sort. These mechanisms are sometimes remarkably sophisticated systems, and are extremely variable in design and capability depending on the species of fish.

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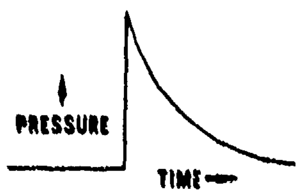
[1] Christian, Ermine A., "The Effects of Underwater Explosions on Swimbladder Fish," Naval Ordnance Laboratory Report NOLTR 73-103, 27 July 1973

The classical approach to developing a damage model for swimbladder fish would require that we know in detail the response of the organ when it was subjected to an explosion pressure field. Considering the wide variations in swimbladder designs among various species, such an approach would lead to an extremely complex model, and would require a vast amount of biological data that is not now in hand. Furthermore, such a detailed model would not necessarily be the most suitable one for general use, since there are non-homogeneous fish populations in most of the locations of practical interest. Consequently, we have started with a less ambitious approach, and have tried initially to define a simple method of linking predictable explosion parameters with swimbladders in general.

The explosion pressure pulse that causes damage is shown in Figure 1. This is the kind of pressure wave generated by a typical underwater explosion in free water. The pressure rises steeply to a high peak value and then decays exponentially. The duration of this wave is very short. Both the duration and the amplitude of the peak pressure depend upon the cube root of the weight, W, and the range from the charge, R. For example, at a 100 ft range from the explosion of a 1-lb charge, the peak pressure would be about 120 lbs per square inch and the duration only about .16 milliseconds. At that same location, if the charge weighed 1000 lbs, the peak pressure in the wave would be about 1600 lbs per square inch, and the duration about 1 millisecond, still quite short.

NOL



SHOCK WAVE FROM UNDERWATER EXPLOSION

PEAK PRESSURE $f\left(\frac{W^{1/3}}{R}\right)^{1.13}$

DURATION $f\left(\frac{R}{W^{1/3}}\right)^{0.22}$

AT RANGE OF 100FT.

CHARGE WT.	PEAK PRESSURE	DURATION
1 LB.	120 p.s.i.	0.16 MILLISEC
1000 LB.	1600 p.s.i.	1 MILLISEC

Figure 1

Naturally, one tends to equate the damaging power of such a shock wave with its maximum amplitude, at the peak. For the most part, past attempts to correlate fish damage with an explosion shock wave have used this peak pressure as the critical explosion parameter. It would be very convenient if this were a suitable damage criterion, because peak pressure is the most predictable of explosion parameters. But peak pressure, alone, does not adequately define the damage field for swimbladder fish.

Fish can withstand compression waves of surprisingly high amplitude without permanent damage. They cannot, however, survive even fairly low-amplitude decompression, or tension. In fact, this seems to be true for most living tissue.

Interestingly enough, the type of damage that an underwater explosion inflicts on the swimbladder also appears to be due to decompression, rather than to compression. The swimbladder is over-extended; it explodes, rather than implodes due to the pressures in the water. This suggests that negative pressures associated with the explosion are more damaging than the shock waves themselves.

Negative pressures are generated in the water by the reflection of the shock wave when it reaches the surface. Upon reflection the outgoing compression wave is inverted as shown in Figure 2, and becomes a tension wave. Near the water surface, at a point such as "A" in Figure 2, we find a composite wave form, like that shown at the lower right. The maximum tension in this composite wave is ΔP, the sum of the positive and negative wave components at this point.

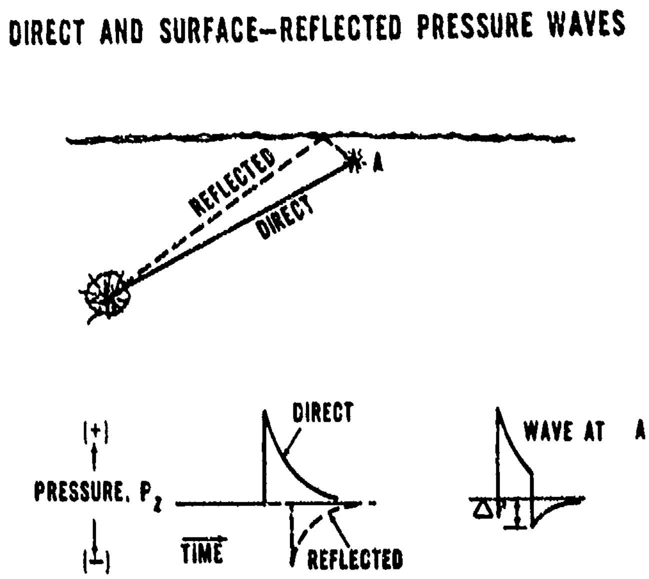


Figure 2

Such negative pressure not only disrupts a swimbladder, it may also disrupt the water itself. Water cannot support very much tension. If the negative pressure ΔP is very much greater than the hydrostatic pressure, the water will be cavitated. There is a so-called "zone of bulk cavitation," within which the water is literally torn into many bubbles. It is this explosion phenomenon that I suggest we should correlate with fish damage. In fact, I propose that for our first, crude damage model we equate the two--that is, assume that the zone of bulk cavitation <u>is</u> the region where swimbladder fish may be harmed by an underwater explosion.

With this approach our proposed new damage zones occur in two locations, as shown in Figure 3. A shallow explosion is shown at the left, and a deeper explosion at the right of the Figure. The spherical region surrounding the charge I have called the "immediate kill zone." Its radius depends only on the size of the explosive charge. This is the close-in damage zone where everything will be destroyed. The damage region we are most interested in is the region near the surface, which I have called the "remote damage zone." The thin, broad wing-shaped areas that are shaded represent the theoretical bulk cavitation zones. The boundaries of these zones can be calculated conveniently with a computer program given in a recent NOL report by Gaspin and Price[2].

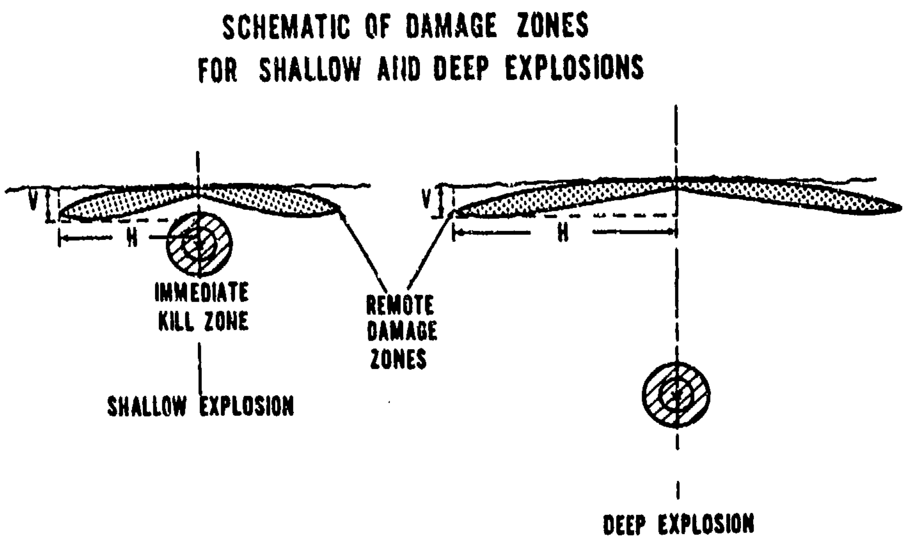


Figure 3

[2] Gaspin, J. B. and Price, R. S., "The Underpressure Field from Explosions in Water as Modified by Cavitation," Naval Ordnance Laboratory Report NOLTR 72-103, 9 May 1972

For making damage range estimates I have boxed in the cavitation region as shown in Figure 3 and used a disc, of radius H and thickness V. We would expect that the probability of fish damage would be highest at the center of this disc, just above the charge, and would taper off towards the outer boundaries where the cavitation becomes less violent. Until we have obtained some data on this question, however, we will assume that the entire region is hazardous to swimbladder fish.

As indicated in Figure 3, the horizontal span of the remote damage zone, H, is larger for the deep than for the shallow explosion. For charges weighing less than about 1000 lbs and detonated shallower than about 50 ft, the dimensions H and V can be approximated by the following simple equations:

$$(W < 1000 \text{ lb}, D < 50 \text{ ft})$$

$$H = 70\sqrt{D} \quad W^{0.02\sqrt{D}}$$

$$V = 8\, W^{0.3}$$

As you can see, for shallow charges, H increases as the depth, D, increases; but is is very insensitive to the charge weight, W. The thickness of the damage zone, V, does not depend on the charge depth, but varies roughly as the cube root of the weight.

For larger charges and greater depths than those indicated, these approximations are not correct. One must actually calculate the boundaries of the bulk cavitation zone in order to estimate the damage region.

It is interesting to compare our new damage zone predictions with an earlier prediction based on a peak pressure damage criterion for a 2000 ton explosion at a 3000 ft depth, a charge weight and depth that are typical for a Deep Water Dump[3].

In a 1970 publication entitled "Ocean Dumping: A National Policy," the President's Council on Environmental Quality (or "CEQ") has this to say on the effects of explosions from dumping munitions:

> "The Department of Defense calculates that detonation of 1000 tons of explosives--the approximate amount contained in the September 4, 1970, "Deep Water Dump" off Washington state--generates a shock wave that will kill most marine animals within 1 mile of the explosion and will probably kill those fish with swimbladders out to 4 miles from the explosion."

That predicted damage radius of 4 miles for swimbladder fish is based on the assumption that a peak pressure of 70 psi will be lethal. The same 70 psi value gives a lethal radius of about 5 miles for a 2000 ton explosion. By contrast, our new damage model predicts a remote damage zone that is only 250 ft thick and has a radius of less than 2 miles. From overall consideration of the limited data in hand, I would also estimate that the immediate kill zone would not extend much more

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[3] See papers on Deep Water Dumps by Stultz and Christian, this volume.

than 1/2 mile, if that, from the explosion. Thus, the model described here predicts that the hazardous area within the water column is only about 10% of the area predicted for this explosion by the CEQ.

This comparison illustrates one of the important reasons for developing a realistic prediction model.

In conclusion I must point out that our predictions of the remote damage zone have not yet been checked experimentally. The new predictions appear to be in reasonable agreement with available experimental results, but the limited fish-kill data do not allow a true test of the model. At the least, however, the damage zone predictions proposed here agree better with the information that is available than do other prediction rules that we have seen.

The next phase of our work on this task will be a series of experiments that are scheduled for this coming summer. These forthcoming tests are designed to check our assumption that the zone of bulk cavitation corresponds to the region of probable damage for swimbladder fish. Once this assumption is either validated or revised, then we will consider the possibility and the need for refining this first crude prediction model.

SAFE DISTANCES FROM UNDERWATER EXPLOSIONS FOR MAMMALS AND BIRDS

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INTRODUCTION

This report presents the results of tests run to determine the effects of underwater explosions on birds and mammals. The information should be of interest to government agencies and private industry groups required to prepare Environmental Impact Statements in connection with detonating high explosives in a water environment.

The studies involving mammals (Reference 1) were supported by the U. S. Navy Bureau of Medicine and Surgery under the direction of the Explosions Research Department, U. S. Naval Ordnance Laboratory, under contract with the Defense Nuclear Agency, Contract No. DASA-01-71C-0013. The studies determined the far-field immersion-blast effects in sheep, dogs, and monkeys. The animals were subjected to underwater blast with their heads above the surface and at 2- and 10-ft depths. Although the studies were run with terrestrial mammals and was aimed at establishing safe ranges for swimmers, the results were applied in this paper to formulate underwater-blast criteria for aquatic and marine diving mammals.

The investigations on bird response to underwater shock (Reference 2) were supported by the Defense Nuclear Agency, STMD, Contract No. DASA-01-70C-0075. The investigations determined the response of birds to underwater blasts while on the surface and at 2-ft depths. The duck was chosen as a model to represent swimming and diving birds. Blast criteria were derived that related underwater blast impulse levels that were safe, that produced injuries, and that were lethal for birds on and beneath the water surface. Graphs were presented giving the slant ranges from underwater explosions associated with the impulse-criteria levels as a function of charge weight, depth of burst, and depth of the biological specimens.

The experimental work discussed in this manuscript was conducted according to the principles enunciated in the "Guide for Laboratory Animal Facilities and Care," prepared by the National Academy of Sciences—National Research Council.

METHODS

<u>The Test Pond Facility.</u> The test pond measured 220 by 150 ft at the water surface and was 30 ft deep over its 30- by 100-ft center portion. The entire pond was lined with black polyvinyl plastic 20 mils thick. A 6-inch-deep layer of sand was located beneath the plastic in the 30-ft-deep part of the bottom. The sides of the pond had a 2-to-1 slope. Two sets of rigging spanned the pond in a north-south direction. The main rigging, located 80 ft from the west end, consisted of a grid 14 by 24 ft which could be raised and lowered by cables on the south bank. Most of the tests were run with animals and gauges beneath the main rigging and the explosive charges were located toward the east. The test pond contained approximately

3.2 million gallons of tap water. The ambient air pressure at the test pond was 12 psia.

Explosive Charges. The explosive charges used were bare spheres of cast Pentolite and TNT and 1-lb blocks of pressed TNT. The charges were detonated at 10-ft depths with electric blasting caps, DuPont No. E-99. The charge weights were designated as 0.5 lb, 1 lb, 3 lb (actually 2.6 lb), and 8 lb.

Pressure-Time Measurements. There were four channels of pressure-time measuring instrumentation. The methods and equipment used for measuring and recording the underwater-blast wave were basically those described in References 1 and 2. The gauges (NOL) consisted of four 1/4-inch tourmaline discs mounted in a Tygon® tube filled with silicone oil. Signals from the gauges were passed through a cathode follower and recorded on a dual-beam oscilloscope. The rise time of the gauges was on the order of 4 μsec. The information from each pressure-time record was fed into a computer program that calculated the peak pressure, impulse, energy, theta, and cut-off time. This was done for both the incident shock and the bottom reflections.

Mammal Tests. One hundred and one Columbia-Rambouillet female sheep, 37 Dalmation dogs, and 6 rhesus monkeys were utilized on these tests. In general, three animals were exposed per test, mounted vertically in the water, long axis perpendicular to the surface. The depth at which sheep and dogs were placed was measured from the water surface to their xiphisternum. Monkeys were submerged to about their neck (glottis) level, shoulders beneath the surface, and were designated as 1-ft depths. About one-third of the sheep were tested at 2- and 10-ft depths. All animals were right-side-on to the charge. All the test subjects were autopsied two hours following the test. At postmortem, the entire length of the G. I. tract was carefully examined. It was slit open, its contents washed out, and the condition of the mucosal lining in the contused areas was recorded.

Eight tests with 24 dogs were run specifically for eardrum response data. Dogs were used because the size and geometry of their eardrum and middle ear approximate man's more so than other animals. The dogs were oriented vertically in the water with their ears exactly at a 1-ft depth. They were right-side-on to the charge with their right ear facing the charge. In order to maintain the exact position of the head, freshly sacrificed animals were used. After sacrifice, the pinna of the ear was clipped to approximate the size of the human's.

Bird Tests. Eighty-one Mallard ducks with a mean body weight of 1.16 (0.89-1.49) kg and nine Rouen ducks with a mean body weight of 2.33 (1.92-2.84) kg were used in this study. Eight Mallards and two Rouens served as controls to check out the effects of handling and placing them beneath the surface for 25 sec. There were two or three birds on each shot. They were always oriented right-side-on to the charge. The distance from the ventral surface of the ducks to the surface of the water was taken as their immersion depth. The majority of the animals were mounted in holding devices that consisted of 14- by 24-inch frames constructed from 3/8-inch steel rods. The birds were placed in harnesses made of 2-inch mesh nylon and suspended in the frames by 1/8-inch nylon cords.

Forty-eight Mallard ducks at 2-ft depths were placed at 7 ranges within the lethal zone. The purpose was to correlate mortality with impulse and ascertain the nature of the lethal immersion-blast injuries. Those that survived were observed for 14 days to find out if birds with serious underwater-blast injuries followed the same pattern as mammals surviving air blasts; namely, few, if any, delayed deaths and a relatively rapid recovery time of 1-2 weeks.

Twenty-seven Mallard ducks were tested at 2-ft depths, at 4 ranges beyond the lethal zone, to establish threshold injury and safe impulse levels for birds beneath the water surface. They were autopsied at 2 hours in order to evaluate very minor lesions that heal rapidly.

Nine Rouen and six Mallard ducks were subjected to underwater blasts while held on the surface at a depth of 0.25 ft (the measured draft of a floating duck). The ducks were tested at 12 ranges to determine lethal, injurious, and safe conditions for birds on the surface.

RESULTS AND DISCUSSION

Mammals. Figure 1 summarizes the injuries in mammals beneath the surface in relation to impulse and slant range from the explosion. All the data were adjusted to the slant range from a 1-lb charge, detonated at a 10-ft depth, and the impulse at a 1-ft depth. The moderate injuries were a slight degree of lung hemorrhage and submucosal contusions of the G. I. tract. The submucosal contusions usually ulcerated the inner lining of the G. I. tract. These contusions were small in area and mostly less than 1/2 sq. in. Moderate injuries occurred out to ranges where the impulse was 20 psi· msec.

The slight lung injuries were petechial lung hemorrhages and mild contusions of the G. I. tract (contusions without ulcerations of the mucosal lining). Slight injuries occurred down to impulse levels of 10 psi. msec. There were no injuries at impulse levels of 6 and less. Between 6 and 10 psi· msec, there were few cases of petechiation or hyperemic areas in the G. I. tract.

Figure 1 indicates that eardrum rupture could occur at 14 psi· msec. This value represents the lower confidence level associated with a 1-percent probability of eardrum rupture. It was taken from the results of a probit analysis run on the dog data. The 50-percent probability of eardrum rupture was 23 psi· msec for the ear that faced the blast--the worst case.

Figure 1 also gives underwater-blast criteria for mammals located beneath the water surface. The safe-impulse criteria was 5 psi· msec.

Birds. The injuries recorded in ducks killed by the underwater blast fitted the pattern found in mammals dying from air or underwater blast. The birds had extensive lung hemorrhage, coronary air embolism, ruptured livers, and perforated eardrums. Unlike mammals, their kidneys were commonly ruptured by the blast and over half the ducks had perforated air sacs.

Birds that survived near LD_1 impulse levels would appear unhurt from external signs but would have sustained internal injuries of moderate severity. There were no delayed deaths in a group of 28 ducks that survived blast in the lethal zone. They all appeared normal at 14 days. At autopsy all the air sacs and eardrums were intact. There was still some remnants of blood clots around their livers and kidneys and some discolorations in their lungs.

Figure 1 gives the mortality and injury levels in ducks tested beneath the surface of the water in relation to impulse and slant ranges. The impulse was adjusted to that measured at a 2-ft depth from a 1-lb charge detonated at a 10-ft depth. As seen in the figure, mortality (1 percent) occurred out to 36 psi· msec. At an impulse of 20 psi. msec, there would be slight lung injuries in about half the cases and a 50-percent probability of eardrum rupture. There would be no injury in birds that received 6 psi· msec and less.

Birds on the water surface were relatively unaffected by the underwater explosion. Probably because their vulnerable organs (lungs and kidneys) are partly above the water line being located along the vertebral column. As seen in Figure 1, birds on the water surface were not injured at a 30-ft range from an 8-lb charge--impulse of 30 psi·msec--at a 3-inch depth. Impulse levels on the order of 40 psi·msec were required to produce slight injury to the lungs and kidneys. Birds had to be within 15–20 ft from the 8-lb charges before receiving extensive or lethal injuries. Three ducks subjected to impulses of 95, 77, and 42 psi·msec flew immediately postshot. They had fish lines attached to their feet. One duck given 100 psi·msec would not fly. Criteria for birds on the water surface are given in Figure 1.

Figure 2 presents a family of curves to use in finding the ranges at which a given impulse at a specified depth will occur. To enter the graph, first calculate the quantity depth of charge x depth of subject/charge weight$^{2/3}$. Second, calculate the scaled impulse/charge weight$^{1/3}$. Third, read off the scaled slant range on the Y axis where the impulse intersects the curve. Divide the scaled range by the cube root of the charge weight to get the slant range. An example follows:

Wanted: The slant range from a 2,000-lb charge, depth of burst 80 ft, where 6 psi·msec would occur at a depth of 20 ft. First solve the quantity:

$$\text{Depth of Charge x Depth of Subject/Charge Weight}^{2/3}$$

$$80 \times 20/2,000^{2/3} = 10$$

Second solve:

$$\text{Impulse/Charge Weight}^{1/3}$$

$$6/2,000^{1/3} = 0.5$$

Third, read the scaled range of 280 on the Y axis where 0.5 on the X axis intercepts the curve for 10:

$$\text{Scaled slant range} = \text{Slant range/charge weight}^{1/3}$$

$$280 \times 12.6 = 3528 \text{ ft}$$

References 1 and 2 contain detailed effects data with matching pressure-time parameters. In addition, the application of the underwater-blast criteria are discussed.

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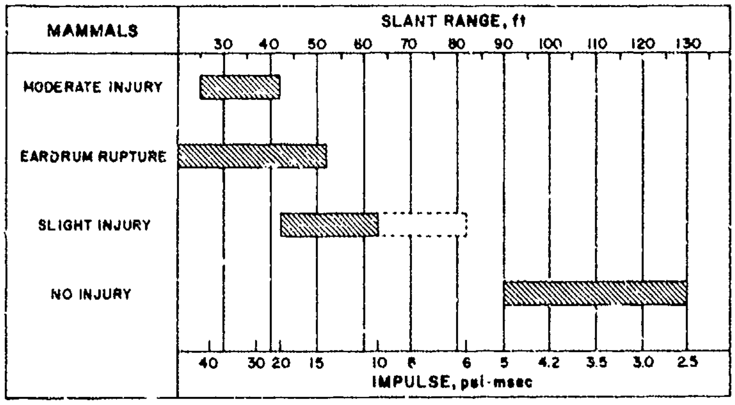
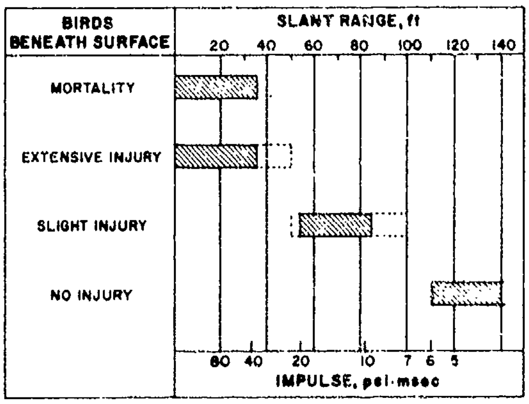
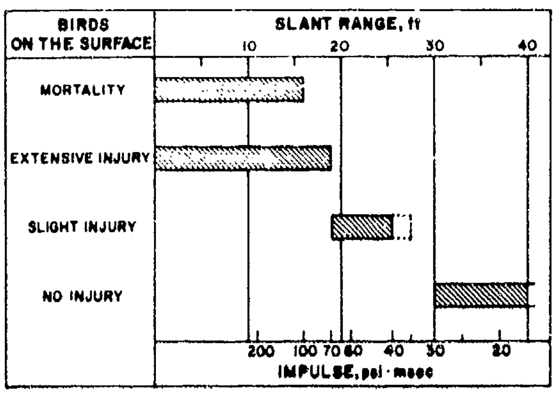


MAMMALS BENEATH THE WATER SURFACE	
Impulse, psi·msec	Criteria
40	No mortality. High incidence of moderate blast injuries including eardrum rupture. Animals should recover on their own
20	High incidence of slight blast injuries including eardrum rupture. Animals would recover on their own
10	Low incidence of trivial blast injuries. No eardrum rupture
5	Safe level



BIRDS BENEATH THE WATER SURFACE	
Impulse, psi·msec	Criteria
45	50% mortality. Survivors seriously injured and might not survive on their own
36	Mortality threshold (LD_1). Most survivors moderate blast injuries and should survive on their own
20	Slight blast injuries and a low probability of eardrum rupture
10	Low probability of trivial lung injuries and no eardrum rupture
6	Safe level



BIRDS ON THE WATER SURFACE	
Impulse, psi·msec	Criteria
130-150	50% mortality. Survivors seriously injured and might not survive on their own
100-120	Mortality threshold (LD_1). Most survivors moderate blast injuries and should survive on their own
40-60	Slight blast injuries
30	Safe level

FIG. 1 EFFECTS IN RELATION TO IMPULSE AND RANGE ALONG WITH CRITERIA FOR MAMMALS AND BIRDS.

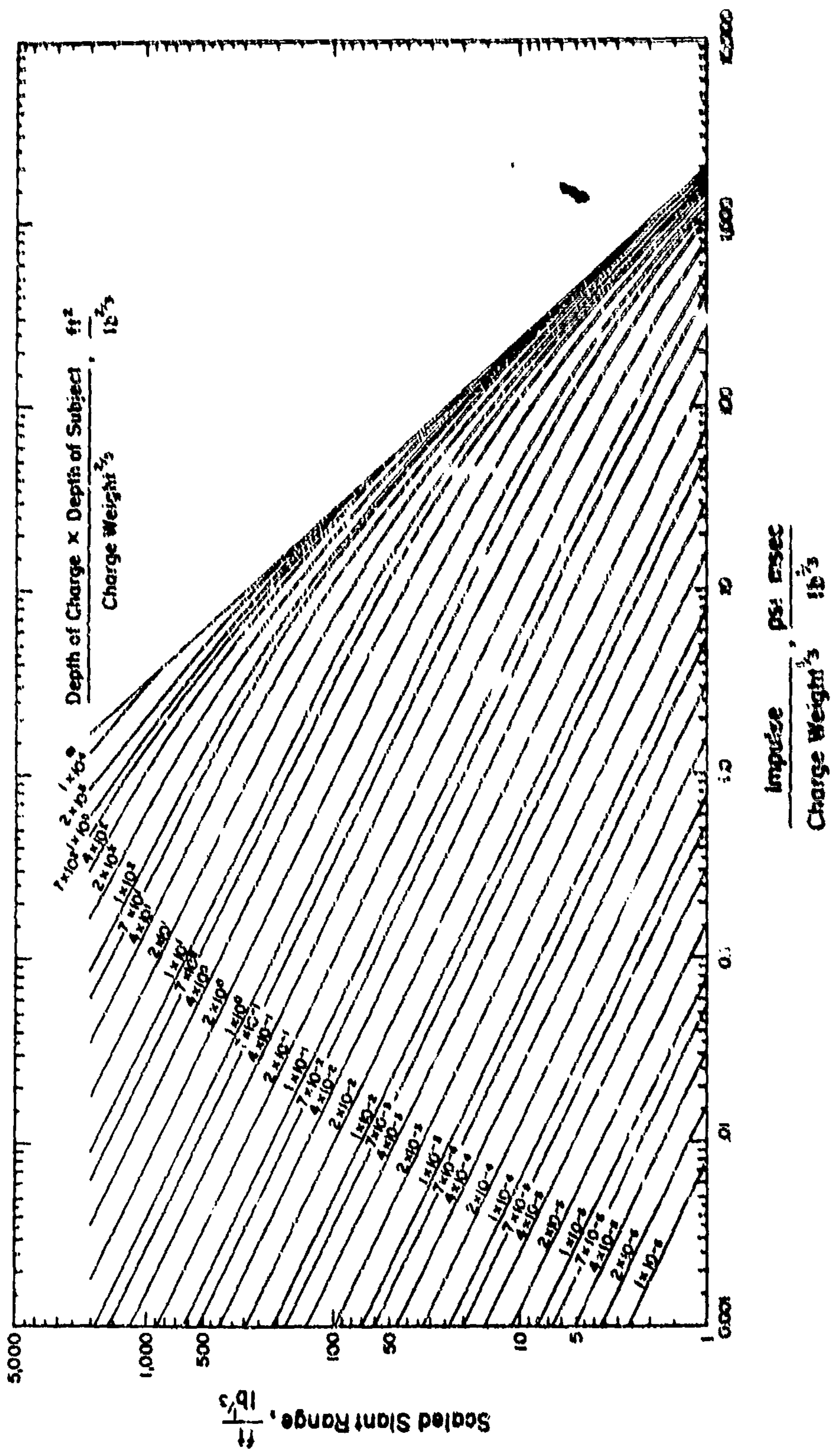


FIG. 2 CURVES TO BE USED IN DETERMINING RANGES FOR GIVEN IMPULSES

RESULTS OF UNDERWATER DEMOLITION ON THE ENVIRONMENT IN A SMALL TROPICAL MARINE COVE

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ABSTRACT

Construction in a shallow cove on Cross Cay, a small island located off eastern Puerto Rico, necessitated the use of 4,000 lbs of explosives for the blasting of a beach area and the removal of underwater and awash coral heads and boulders. In order to assess the impact on the environment, measurements were made of acoustic pressure levels and the effect of the demolition on marine life. Three separate detonations occurred venting a large portion of the energy skyward. At a distance of 350 yards from the demolition area, the largest of the three blasts produced a pressure level of 9.15 lbs/in^2. Air bladdered fish suspended in cages at 175 yards and 350 yards from the explosions remained alive and healthy. Damage to the environment was heaviest in close proximity to the demolition area where a number of fish were killed. Two hours after the last explosion small schools of fish were observed in the blasted area. It was felt that all the necessary precautions were taken to keep the damage to the environment minimal.

NOTE: The material presented in this talk is in the following publication: "Effects of Underwater Demolition on the Environment in a Small Tropical Marine Cove" by Charles L. Brown, Jr. and Raymond H. Smith, NUSC Technical Report 4459, 11 December 1972, Naval Underwater Systems Center, Newport, Rhode Island 02840

Benthic Ecological Studies at Deepwater Dumpsite G
in the Northeast Pacific Ocean
off the Coast of Washington

Andrew G. Carey, Jr.*, James B. Rucker#, and Ronald C. Tipper+

ABSTRACT

As a part of the 1971 environmental survey of the Navy deep water munitions dumpsite G, several components of benthic fauna were sampled on a transect of five stations on the northern Cascadia Abyssal Plain in the Northeast Pacific Ocean approximately 167 km west of the Strait of Juan de Fuca. From 1969 to 1970, five ship hulks, loaded with out-dated munitions, were scuttled in the dumpsite area. The major objective of the environmental survey was to determine if the sea floor environment and biota had been permanently damaged by the detonation during sinking of the five lots of munitions and by the presence of corrosive products from the debris and by-products from the explosions.

Benthic organisms were sampled and studied as possible indicators of environmental quality. Infauna were collected by a 0.1 m^2 Smith-McIntyre grab, and mega-epifauna by a three-meter beam trawl. Certain mega-epifauna were studied by analysis of bottom photographs taken along the trawl tracklines. Abundance and species composition were determined and were correlated with environmental data including distance from the debris areas. No general trends in faunal composition or abundance can be directly attributed to ordnance dumping at DWD-G. Definite conclusions cannot be drawn, however, because no pre-dump survey was undertaken. There were indications that there may have been local environmental changes in trace metals immediately adjacent to a debris site, and perhaps some faunal changes within a debris area. There were no significant differences in infaunal composition or abundance between stations near the debris zone and at corresponding depths up to 20 nmi away, though there were general north-south changes in the mega-epifaunal community.

The Deepwater Dumpsite - G at the base of the Nitinat deep-sea fan on the Washington continental slope supports a more abundant mega-epifaunal community than is found in similar environments to the south, off Oregon.

INTRODUCTION

From 1964 to 1970 the U.S. Navy disposed of obsolete and out-dated munitions at designated deepwater dumpsites by sinking them in the hulks of World War II liberty ships. Nineteen Deep Water Dump (DWD) operations were completed before September 1970. Because of a concern about possible environmental effects of such deep-sea waste disposal techniques, a consequent moratorium on further DWD operations was put into effect by the Secretary of the Navy in September 1970. In 1971-72 the U.S.

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Navy undertook comprehensive environmental research to determine if the deep-sea munitions disposal practices had caused significant, long-term deterioration of the environment and biota in the dumpsite areas and adjacent ocean regions.

Deepwater Dumpsite G, located 90 nmi (167 km) west of Cape Flattery, Washington was chosen as the study area for determination of the environmental effects of exploded cargoes. It is located in Cascadia Basin near the north-western edge of the Nitinat Deep-Sea Fan at a water depth of 2500-2600 m (Fig. 1). Five DWD operations, numbers XVI through XX totaling over 31,000 tons, took place between August 1969 and September 1970 at this site. In each case extensive spontaneous explosions occurred in the cargo, demolishing the ships involved. The remains of all five hulks were located on the sea floor by a towed magnetometer and side-scan sonar during a survey undertaken previous to the environmental research (Spiess and Sanders, 1971). The nearly circular patches of debris were verified through photography and were accurately mapped with the use of satellite and Loran A navigation and bottom transponders.

The environmental survey and assessment was initated with a cruise aboard the USNS De Steiguer in September 1971. The sampling plan had been chosen to document as effectively as possible the condition of the environment and biota at the DWD site and to provide some manner of comparison to conditions existing in the area prior to the munitions disposal. Specific predump surveys had not been conducted by the Navy, and the historical data were lacking or were insufficient for valid comparisons with post-dump conditions. Five stations were planned along a transect through the dumpsite area to demonstrate possible changes in the structure of benthic faunal communities or in the concentration of trace elements in the fauna (Fig.2). Two reference stations were located approximately 20 nmi (37 km) to the north and south, far enough away to be relatively unaffected by possible influences from the munitions dumping activities and close enough to minimize possible geographic effects. Two stations were located north and south adjacent to the total dumpsite area. One station was directly adjacent to a debris field within the dumpsite boundaries, as close as safety permitted. As metal fragments were retrieved in bottom trawl collections from Station 1 adjacent to Debris Site 2, these samples were probably obtained close to the actual debris concentrations. Fauna distributions are strongly correlated with depth on the continental slope (Le Danois, 1948; Carey, 1965; Sanders and Hessler, 1969; and Rowe and Menzies, 1969); therefore, the stations were located within a narrow depth range to minimize depth effects. Station 5, the northern reference station, however, is not directly comparable to the other transect stations, because its actual location was at a significantly shallower depth.

Biological sampling was designed to quantitatively sample several components of the benthic fauna. As benthic invertebrate organisms generally move relatively small distances over the ocean floor, they have been used as indicators of environmental quality. Major changes in environmental quality are reflected in the structure of benthic communities (McNulty, 1970). Benthic organisms as concentrators of many trace elements, can be used as indicators of heavy metal and other chemical compounds when such materials are thought to be contaminants in an area.

Infaunal burrowing invertebrates were sampled with a 0.1 m^2 Smith-McIntyre bottom grab (Smith and McIntyre, 1954); three such samples were taken at Station 1 and five taken at each of the other four major stations (Table 1). Infaunal grab samples were washed on board ship through 1.0 and 0.42 screens immediately upon

retrieval to concentrate the fauna by washing out the finer sediment particles. Samples were preserved in 10% buffered formalin until later processing in the laboratory when they were swithched to 70% ethanol. In the laboratory the macrofaunal organisms, 1.0 mm or greater in size, were picked from the samples, sorted, and identified as far as possible (Carey, Hancock, and Paul, 1972).

Mega-epifauna organisms living in, or associated with, the sediment surface were sampled with a 3 m quantitative beam trawl (Carey and Heyamoto, 1972) equipped with odometer wheels and a 0.5 in (1.3 cm) stretch mesh otter trawl-type net. Two samples per station were collected, though samples number 3 and 6 were discarded because of inadequate sample size (Table 1). The samples were preserved in 10% buffered formalin at sea and were picked, sorted, and identified in the laboratory (Carey, Hancock, and Paul, 1972).

The abundance of certain of the mega-epifauna was independently determined through the use of a stereo deep-sea photographic system (Pollio, 1969). One hundred stereo pairs of bottom photographs were planned from areas parallel to the beam trawl track lines. The photographs were analyzed for the large epibenthic organisms associated with the sediment surface. Knowledge of the mega-epifauna acquired from bottom trawl samples at the DWD study area and at a large series of stations further to the south on Cascadia Plain has enabled us to identify much of the larger fauna observed in the bottom photographs. The organisms on each stereo pair of photographs were counted and identified as far as possible after the area of non-overlap was determined for each pair of photographs and for each of the overlapping pairs in the continuous photographic transect. Only the field of view with good resolution was utilized for the quantitative counts.

The environment is similar at the first four benthic stations. Samples were taken of the water overlying the bottom and of the sediments, and analyses of various environmental characteristics undertaken. The sediments from the five stations are silty-clays with the average grain size composition varying less than 10% between samples and stations. The sediment is uniform in the dumpsite area and averages 1% sand, 27% silt, and 72% clay. The organic carbon content of the sediments ranges from 1.5 to 1.8% by weight. Water content of the sediments does not demonstrate a definite pattern of lateral geographic variation (Kravitz _et al_., 1971).

The water immediately overlying the sea floor in the study area is Subarctic North Pacific water. The temperature is about 1.6°C at 2500 meters depth. Salinity is 34.60‰ and oxygen is about 1.7 ml/L at 2500 m depth. There is no significant difference between stations 1 through 4 in characteristics of the overlying water, though differences are apparent at Station 5 (U.S. Office of the Oceanographer of the Navy, 1972).

We gratefully acknowledge funding support from the U.S. Navy through the Office of Naval Research (Contract No. N000 14-67-A-0396-0009), and the helpful research cooperation of the U.S. Naval Oceanographic Office. We thank R.R. Paul for assistance at sea and in the laboratory, D.R. Hancock for identification of the polychaetes and invaluable research assistance, N. Cummings and V. Spear for processing the biological samples, R.C. Carney for identifying holothurians, and R.E. Ruff for identifying mega-epifauna and analyzing bottom photographs.

RESULTS

Infauna

Polychaete worms are the most abundant members of the infaunal community at all five stations with molluscs and arthropods second and third most abundant, respectively (Fig. 3). The polychaetous annelids were identified to 35 species from 30 genera; most are ubiquitous, eurybathic forms. Each station had a high percentage of polychaete species common with the other stations. Excluding Station 5 because of its anomalous shallow depth, there does not seem to be a significant difference in the polychaete fauna between station 1 through 4. There is a high variance of polychaete abundance between samples at each station, as great or greater than between-station variance. The infaunal polychaetes must be patchy in distribution, or were too few in numbers to be adequately sampled by the 0.1 m^2 grab sampler. The composition of the fauna by phyla demonstrates changes in the minor components at the stations. Molluscs are more abundant along the northern half of the transect at Stations 1, 2, and 5, while arthropods are relatively more numerous at the southern two stations (No. 4 and No. 3). Echinoderms were collected by the grab only at stations 1 and 2, directly adjacent to, and just north of the debris sites.

In general, there is a trend south to north, of increasing infaunal numerical density, though no significant trend in biomass can be demonstrated at the four comparable stations (Figs. 4 and 5). The average numerical density is twice as great at Stations 1 and 2 as at Station 4, the southernmost station. The mean biomass at the stations varied between 1.6 g/m^2 at Station 4 to 2.5 g/m^2 at Station 5.

Epifauna

Echinoderms, particularly ophiuroids (brittle stars), predominate as a group at the northern stations (Stations 1, 2, and 5). Arthropods comprise the most abundant group at the southern two stations (Stations 3 and 4) with isopods being the most numerous (Fig. 6). Reasons for the general trend for increasing numbers of echinoderms and decreasing numbers of arthropods with distance northward are not yet apparent. As only one quantitative sample was obtained at Stations 2 and 4, the data from these stations might be biased by patchy distributions of the fauna. The continued shift in faunal composition with distance could be related to the sampling problem, to some natural environmental gradient, or perhaps to the local disturbance caused by the munitions dumping. The distributions of holothurian species clearly demonstrate the uniqueness of Station 5 (Fig. 7).

There are no clear trends evident in the abundance of the mega-epifauna along the DWD-G environmental transect, though Station 5 has a larger number and biomass of organisms than the four isobathyal stations (Table 2). The numerical density varies between 10,244 and 27,798 individuals per 10^4 m^2, and the biomass between 13,672 and 19,099 g per 10^4 m^2 at the four stations.

The numerical density of certain of the mega-epifauna was also estimated independently by analysis of stereo bottom photographs. The data derived from the beam trawl samples and the photographs agree fairly well; estimates for ophiuroids, for example, are relatively close for the two methods (Fig. 8). Figures 9 through 13 illustrate typical organisms and microtopography present at the DWD-G stations. Estimates for the abundance of larger echinoderm species and for fishes often differ uniformly for a species between trawl and camera data. These differences may be caused by their behavior or their orientation and position in relation to the water-

sediment interface (Carey, in preparation). No ophiuroids were observed in photographs taken by Spiess and Sanders (1971) within the debris zones. These organisms either were not present in the disturbed environment or possibly were not detected in photographs that were taken at a higher altitude above the bottom.

DISCUSSION

Excluding Station 5 because it is about 400 m shallower than the others, none of the trends in faunal composition and abundance can be correlated with the physical features of the benthic boundary. Water characteristics (temperature, salinity, dissolved oxygen, and nutrients) and sedimentary characteristics (textural composition, clay mineralogy, organic carbon content, and mass physical properties) all vary within narrow limits with no general trends along the four station transect through the dumpsite area. These data agree with the ranges reported in the literature for similar environments. Sediments at Station 1 adjacent to a debris field contained the highest concentrations of lead and mercury, and the overlying water well above the bottom contained the highest levels of lead (Yamamoto, Weiss, and Zirino, 1971). The concentrations for Pb and Hg lie within ranges reported in the literature for similar environments. There were no correspondingly high values of trace metals in the benthic organisms at Station 1. The anomalously high concentrations in the environment at Station 1 may be due to the dumping operations, to natural conditions, or to contamination by the water and sediment samplers.

The mega-epifauna are more abundant at the four dumpsite transect stations at the base of the Nitinat Fan than at similar environments to the south off Oregon at the base of the continental slope. Five stations (CP-1-A through CP-1-E) located every 20 nmi (37.4 km) along the slope base from Tillamook Head (45° 56.0' N Latitude) to Yaquina Head (44° 38.6'N Latitude) support fewer mega-epifaunal invertebrate organisms per unit area than the DWD-G environment (Fig. 14). There is a general trend for decreasing numerical abundance of megafauna with increasing distance to the south along the base of the slope off Oregon and Washington. This steady decline in abundance with distance may be related to the increase in depth from 2520 m at DWD-G to 2860 m at Station CP-1-E off central Oregon or to the influence of high sedimentation rates associated with the Nitinat and Astoria deep-sea fans on the continental margin. The general trend suggests that the dumpsite area supports an abundant epifauna for reasons other than the dumping operations. The numerical densities and biomass of infauna at Deepwater Dumpsite G lie within ranges for similar depths elsewhere (Filatova and Levenstein, 1961; Frankenberg and Menzies, 1968; Kuznetsov, 1964; Sanders, Hessler and Hampson, 1965; Zenkevitch, Birstein, and Belyaev, 1955; and Carey, unpublished).

The data from the post-dumping ecological studies do not demonstrate long-term, general detrimental changes to the benthic fauna that can be ascribed to the dumping operations themselves. There are indications, however, that there may be some disturbances within the debris fields, and there are general trends in mega-epifaunal taxonomic composition that remain unexplained. Because of the low numbers of each species, probable patchy distributions, and the necessary low intensity of sampling, it is difficult to describe community structure in fine enough detail to determine if subtle, long-term effects are present from the munitions dumping. The reported results are not conclusive as there were no appropriate baseline data for the benthic

environment and associated fauna previous to the ordnance dumping operations at DWD-G off Cape Flattery, Washington. Any future assessment of the effects of deepwater munitions dumping should include detailed pre and post studies.

CONCLUSIONS

1. There are no marked differences in the infauna between Stations 1, 2, 3 and 4 along the Deep Water Dump site environmental transect.

2. There were general trends in the composition of the mega-epifaunal community along the isobathyal transect from the southern station (Station 4) to the station north of DWD-G (Station 2), but no definite conclusions as to cause can be drawn at this time.

3. There are indications of some local environmental changes immediately adjacent to a debris site, and perhaps some faunal changes within the debris areas, but repopulation after the dumping operations has taken place to a large degree.

4. The Deep Water Dump site G and sea floor adjacent to it at the base of Nitinat deep-sea sediment fan on the Washington continental slope supports a more abundant mega-epifaunal community than similar but slightly deeper environments further to the south off Oregon.

Table 1: Deep-Water Dump Site G Benthos sampling data.

Gear and Number	Station	Position		Depth (m)
BmT 1	DWD 1	48° 18.4' N	127° 04.2' W	2520
BmT 2	DWD 1	48° 18.6' N	127° 00.9' W	2520
BmT 3	DWD 2	48° 21.7' N	126° 55.8' W	2532
BmT 5	DWD 4	47° 50.5' N	127° 02.6' W	2529
BmT 7	DWD 3	48° 07.2' N	127° 04.6' W	2529
BmT 8	DWD 3	48° 07.8' N	127° 04.3' W	2510
BmT 9	DWD 5	48° 38.0' N	126° 58.1' W	2189
BmT 10	DWD 5	48° 38.5' N	126° 58.0' W	2030
Shipek #1	DWD 1	48° 15.2' N	127° 06.0' W	2511
Shipek #2	DWD 1	48° 17.1' N	127° 02.5' W	2551
SMG 3	DWD 1	48° 17.1' N	127° 03.8' W	2551
SMG 4	DWD 1	48° 16.7' N	127° 02.8' W	2551
SMG 5	DWD 1	48° 16.8' N	127° 03.1' W	2551
SMG 6	DWD 2	48° 22.7' N	127° 55.0' W	2532
SMG 7	DWD 2	48° 22.1' N	126° 56.1' W	2532
SMG 8	DWD 2	48° 22.6' N	126° 54.0' W	2532
SMG 9	DWD 2	48° 22.7' N	126° 55.4' W	2532
SMG 10	DWD 2	48° 22.7' N	126° 55.3' W	2532
SMG 11	DWD 3	48° 08.0' N	127° 03.5' W	--
SMG 12	DWD 3	48° 07.7' N	127° 04.5' W	--
SMG 13	DWD 3	48° 08.0' N	127° 05.6' W	--
SMG 14	DWD 3	48° 08.0' N	127° 03.5' W	--
SMG 15	DWD 3	48° 08.5' N	127° 03.1' W	2543
SMG 16	DWD 4	47° 51.3' N	127° 02.6' W	2551
SMG 17	DWD 4	47° 50.0' N	127° 03.4' W	2551
SMG 18	DWD 4	47° 50.8' N	127° 02.8' W	--
SMG 19	DWD 4	47° 49.6' N	127° 02.7' W	2497
SMG 20	DWD 4	47° 50.8' N	127° 02.9' W	2497
SMG 21	DWD 5	48° 37.0' N	127° 22.6' W	1994
SMG 22	DWD 5	48° 37.5' N	127° 00.5' W	1994
SMG 23	DWD 5	48° 37.5' N	127° 00.6' W	1994
SMG 24	DWD 5	48° 37.2' N	127° 00.8' W	1994
SMG 25	DWD 5	48° 36.2' N	127° 03' W	--

BmT - Beam Trawl SMG - Smith-McIntyre Grab

Table 2: Estimates of total abundance of mega-epifaunal invertebrates (>1.2 cm) at dumpsite stations (arranged south to north) with ranges and means.

	Station	Mean	Range	No. of Observations
(A) Numerical Density (no./$m^2 \times 10^4$)	4	20,086	-	1
	3	10,244	7,402-13,085	2
	1	15,017	10,702-19,332	2
	2	27,798	-	1
	5	23,178	6,773-39,584	2
(B) Biomass (g wet wt/$m^2 \times 10^4$)	4	13,672	-	1
	3	15,331	13,938-16,723	2
	1	19,099	11,004-27,193	2
	2	15,936	-	1
	5	26,614	6,904-46,325	2

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FIGURE CAPTIONS

Figure 1. Location map illustrating major topographic features of Cascadia Abyssal Plain, including Nitinat and Astoria deep-sea sediment fans.

Figure 2. Topography of DWD-G with environmental survey stations and debris sites indicated.

Figure 3. Taxonomic composition by phyla of macro-infauna (>1.0 mm) at the DWD-G environmental stations.

Figure 4. Numerical density (no./m^2) of macro-infauna at DWD-G environmental stations. The mean, range, and 1 standard error around the mean are indicated for each station.

Figure 5. Biomass (g wet preserved wt./m^2) of macro-infauna at DWD-G environmental stations. The mean, range, and 1 standard error around the mean are indicated for each station.

Figure 6. Taxonomic composition by phyla of the mega-epifauna at DWD-G environmental stations.

Figure 7. Distribution of holothurian (sea cucumber) species of the mega-epifauna at the DWD-G stations.

Figure 8. Comparison of estimates of numerical abundance of Ophiuroidea (brittle stars) by quantitative beam trawling and stereo bottom photography at the DWD-G environmental stations.

Figure 9. Bottom photograph from station 4. Note the ophiuroid indicated by arrow, the burrows, and faecal castings. (Photo by Pollio)

Figure 10. Bottom photograph at Station 3. Note the sea cucumbers (Paelopatides confundens), the ophiuroid and the faecal casting. The scale is 1 meter. The compass suspended beneath the camera is just above the sediment.

Figure 11. Bottom photograph taken within one of the debris fields. Note the ship debris and the burrows and sea cucumbers present among the wreckage. (Photo by Pollio)

Figure 12. Bottom photograph at Station 2. Note the fish, holothurian, ophiuroid, and the mottled appearance of the bottom caused by bioturbation. The scale is 1 m. (Photo by Pollio)

Figure 13. Bottom photograph at Station 5. Note the plentiful holothurians and ophiuroids. The area analyzed for organisms is indicated by inked lines drawn on the photographic print; the animals are recorded by grease pencil marks on a transparent overlay. (Photo by Pollio)

Figure 14. A comparison of the numerical density of the mega-epifauna (Station 1 through 4) at Deep Water Dumpsite-G and 5 stations at the base of the continental slope off Oregon.

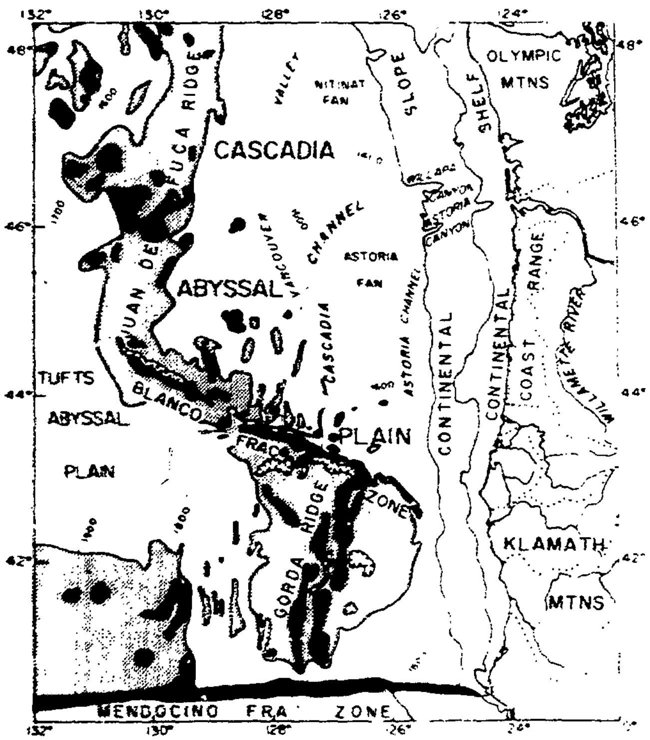

FIG. 1 LOCATION MAP ILLUSTRATING MAJOR TOPOGRAPHIC FEATURES OF CASCADIA ABYSSAL PLAIN, INCLUDING NITINAT AND ASTORIA DEEPSEA SEDIMENT FANS.

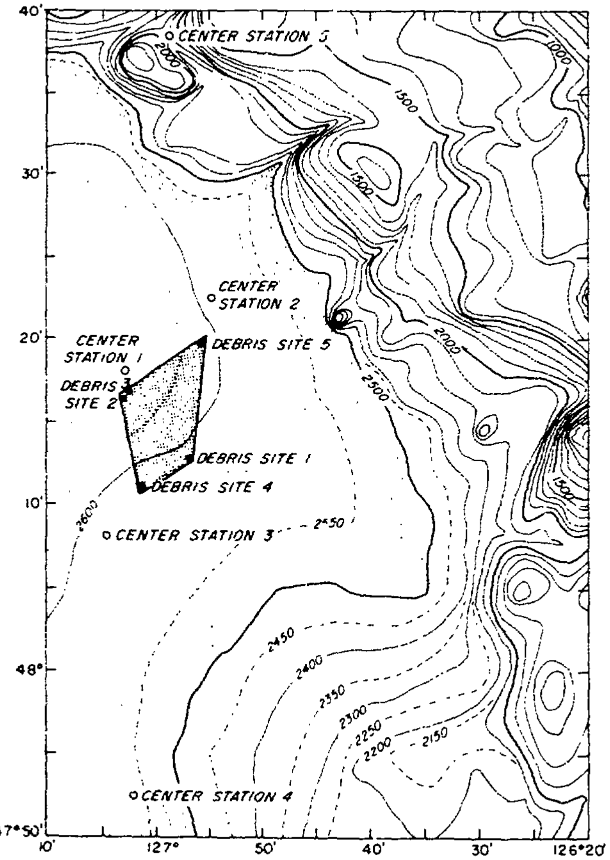

FIG. 2 TOPOGRAPHY OF DWD-G WITH ENVIRONMENTAL SURVEY STATIONS AND DEBRIS SITES INDICATED.

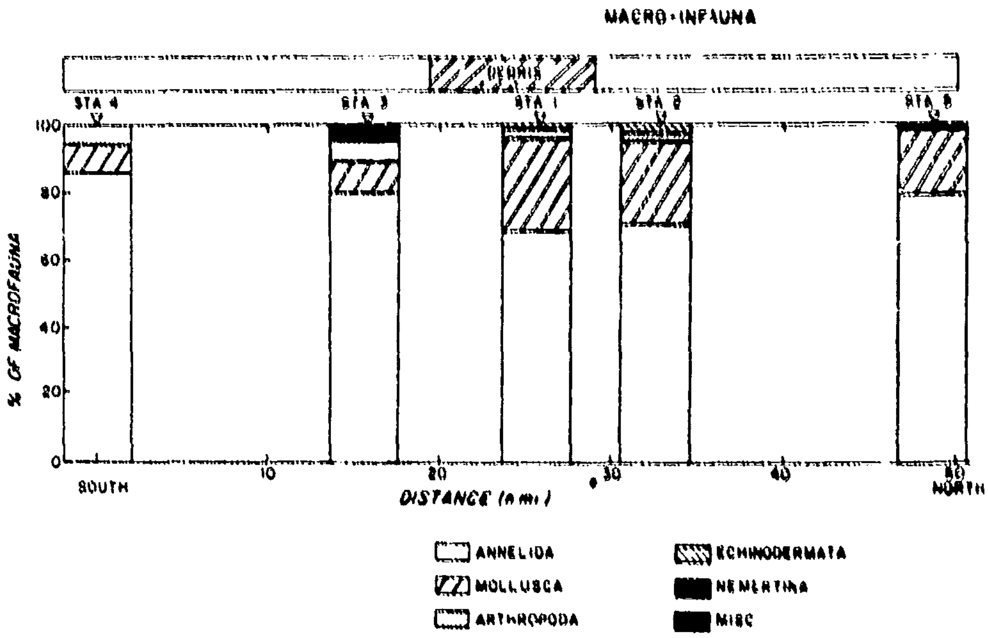

FIG. 3 TAXONOMIC COMPOSITION BY PHYLA OF MACRO-INFAUNA (>1.0 MM) AT THE DWD-G ENVIRONMENTAL STATIONS.

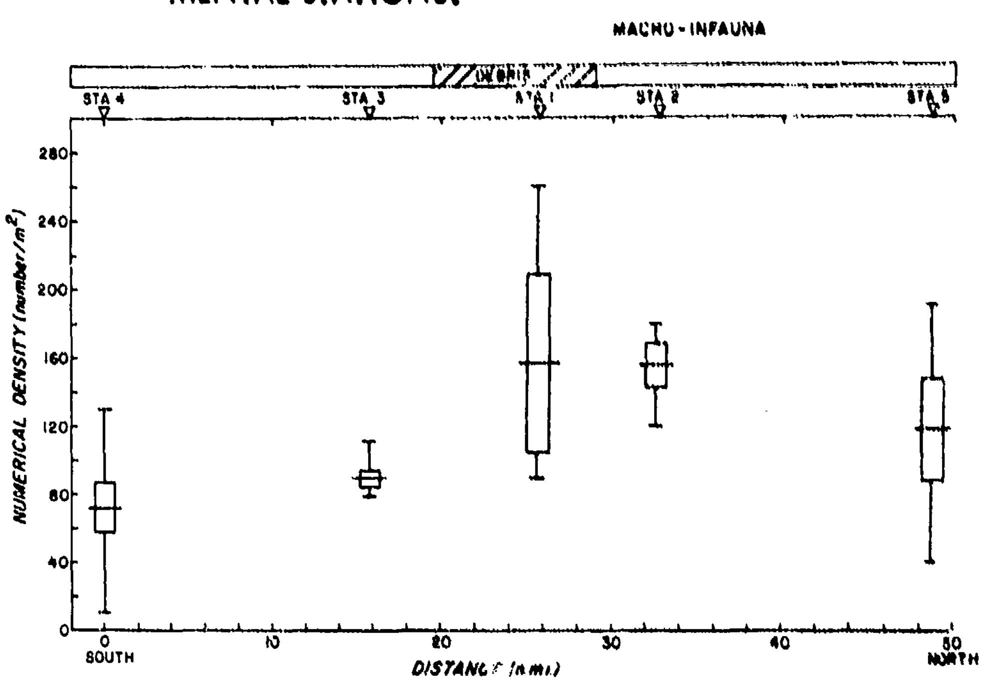

FIG. 4 NUMERICAL DENSITY (NO./M^2) OF MACRO-INFAUNA AT DWD-G ENVIRONMENTAL STATIONS. THE MEAN, RANGE, AND 1 STANDARD ERROR AROUND THE MEAN ARE INDICATED FOR EACH STATION.

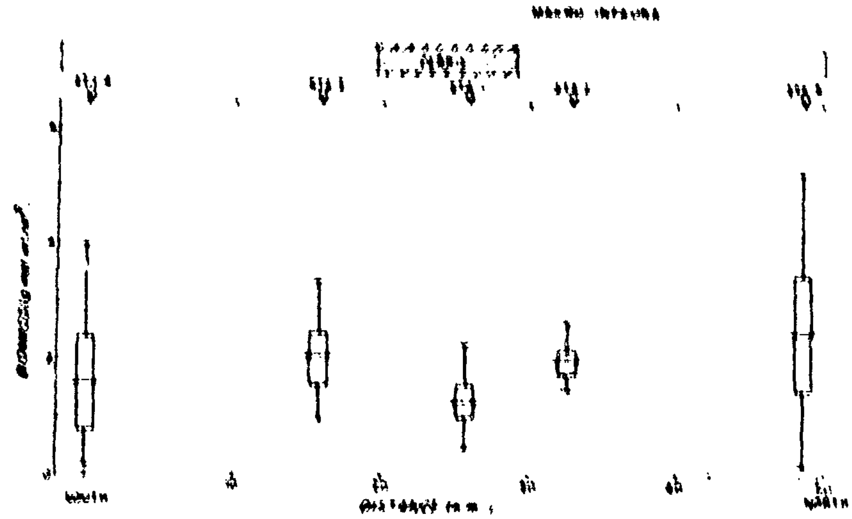

FIG. 5 BIOMASS (G WET PRESERVED WT./M²) OF MACRO-INFAUNA AT DWD-G ENVIRONMENTAL STATIONS. THE MEAN, RANGE, AND 1 STANDARD ERROR AROUND THE MEAN ARE INDICATED FOR EACH STATION.

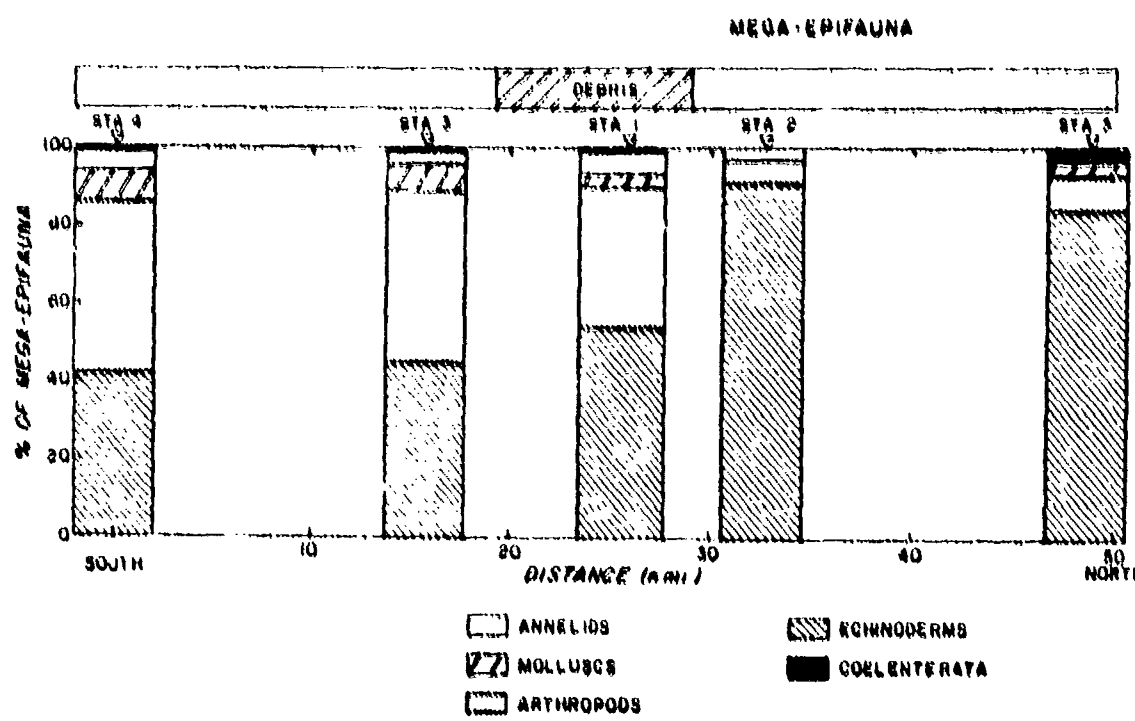

FIG. 6 TAXONOMIC COMPOSITION BY PHYLA OF THE MEGA-EPIFAUNA AT DWD-G ENVIRONMENTAL STATIONS.

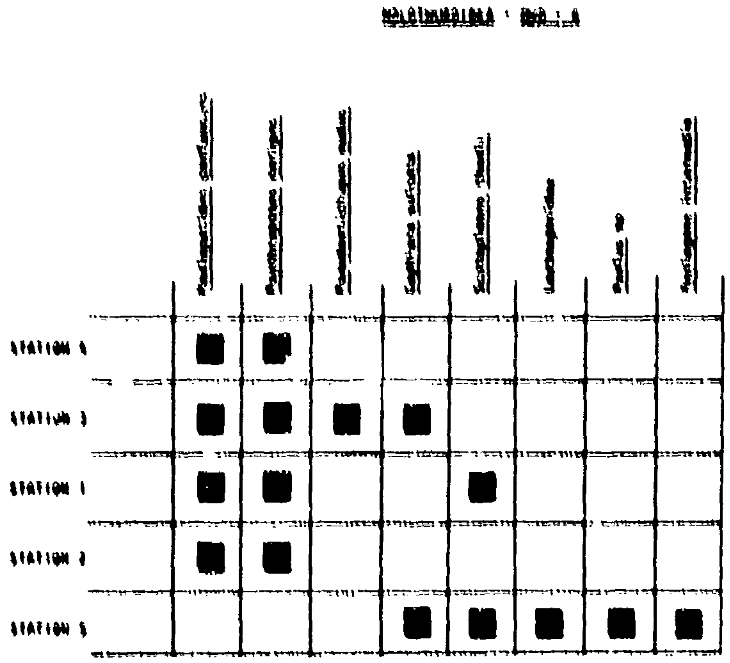

FIG. 7 DISTRIBUTION OF HOLOTHURIAN (SEA CUCUMBER) SPECIES OF THE MEGA-EPIFAUNA AT THE DWD-G STATIONS.

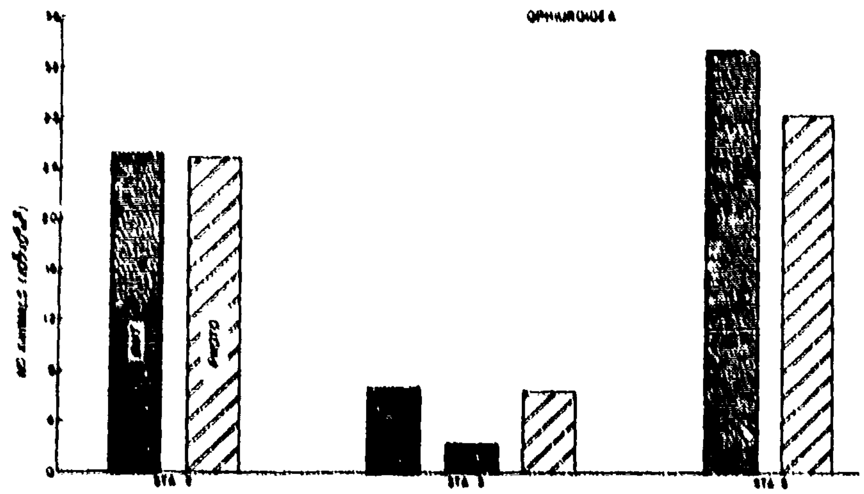

FIG. 8 COMPARISON OF ESTIMATES OF NUMERICAL ABUNDANCE OF OPHIUROIDEA (BRITTLE STARS) BY QUANTITATIVE BEAM TRAWLING AND STEREO BOTTOM PHOTOGRAPHY AT THE DWD-G ENVIRONMENTAL STATIONS.

FIG. 9 BOTTOM PHOTOGRAPH FROM STATION 4. NOTE THE OPHIUROID INDICATED BY ARROW, THE BURROWS, AND FAECAL CASTINGS. (PHOTO BY POLLIO)

FIG. 10 BOTTOM PHOTOGRAPH AT STATION 3. NOTE THE SEA CUCUMBERS (PAELOPATIDES CONFUNDENS), THE OPHIUROID AND THE FAECAL CASTING. THE SCALE IS 1 METER. THE COMPASS SUSPENDED BENEATH THE CAMERA IS JUST ABOVE THE SEDIMENT.

FIG. 11 BOTTOM PHOTOGRAPH TAKEN WITHIN ONE OF THE DEBRIS FIELDS. NOTE THE SHIP DEBRIS AND THE BURROWS AND SEA CUCUMBERS PRESENT AMONG THE WRECKAGE (PHOTO BY POLLIO)

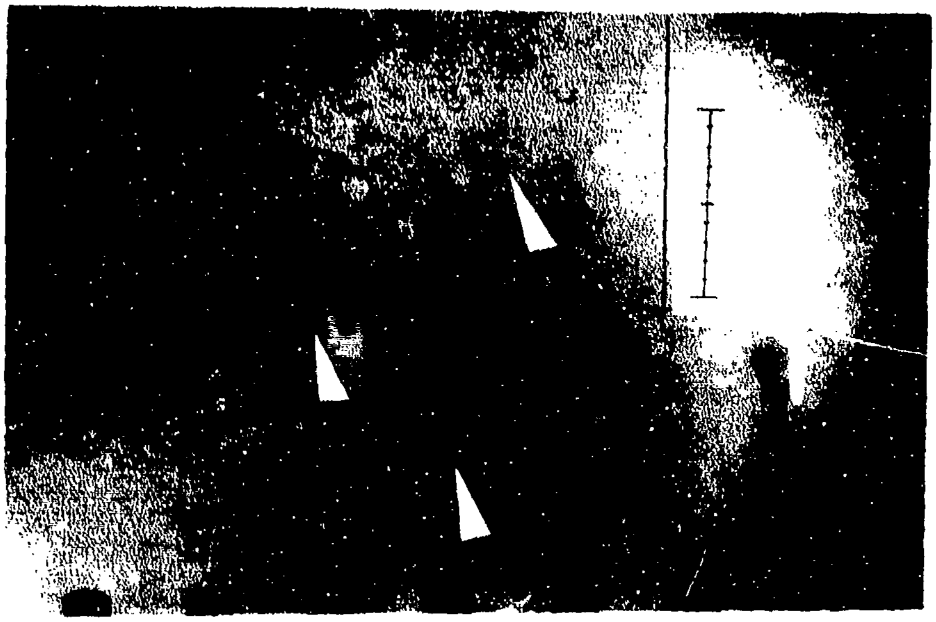

FIG. 12 BOTTOM PHOTOGRAPH AT STATION 2. NOTE THE FISH, HOLOTHURIAN, OPHIUROID, AND THE MOTTLED APPEARANCE OF THE BOTTOM CAUSED BY BIOTURBATION. THE SCALE IS 1 M. (PHOTO BY POLLIO)

FIG. 13 BOTTOM PHOTOGRAPH AT STATION 5. NOTE THE PLENTIFUL HOLOTHURIANS AND OPHIUROIDS. THE AREA ANALYZED FOR ORGANISMS IS INDICATED BY INKED LINES DRAWN ON THE PHOTOGRAPHIC PRINT. (PHOTO BY POLLIO)

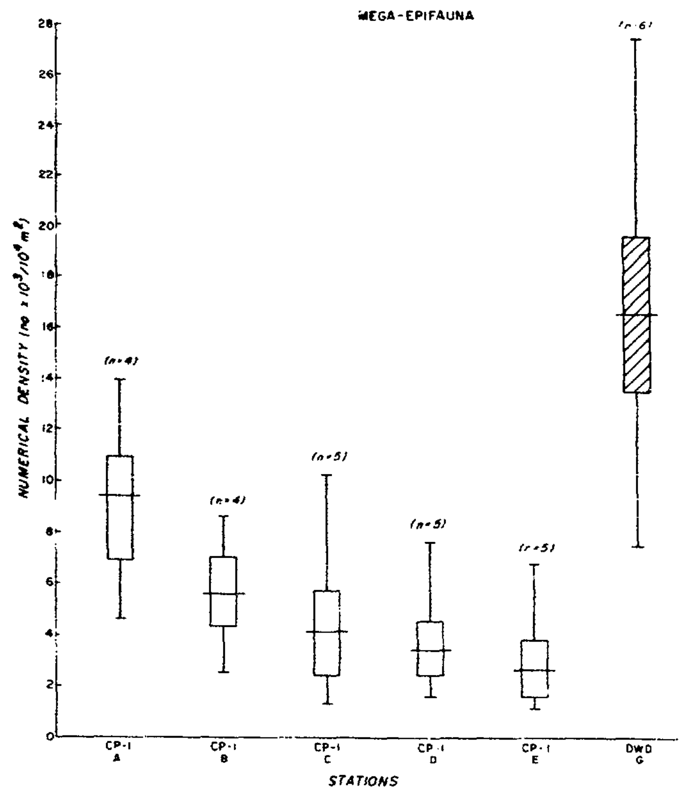

FIG. 14 A COMPARISON OF THE NUMERICAL DENSITY OF THE MEGA-EPIFAUNA (STATION 1 THROUGH 4) AT DEEP WATER DUMPSITE-G AND 5 STATIONS AT THE BASE OF THE CONTINENTAL SLOPE OFF OREGON.

PROJECT TUGBOAT
EXPLOSIVE EXCAVATION OF A HARBOR IN CORAL

by Walter C. Day
Paper Presented by Edward J. Leahy

OBJECTIVES

The U. S. Army Corps of Engineers (CE) and the U. S. Atomic Energy Commission (AEC) have been engaged in a joint research program since 1962 to develop the basic technology necessary to use nuclear explosives in conjunction with the construction of large-scale civil engineering projects. The Explosive Excavation Research Laboratory (EERL) of the Waterways Experiment Station (U. S. Army Engineer Nuclear Cratering Group at the time of the experiment) has been accomplishing the Corps' portion of this joint program. The major part of the program has been the execution of chemical explosive excavation experiments. In the past, these were preliminary to planned nuclear excavation experiments. The experience gained and the technology developed in accomplishing these experiments have led to an expansion of the EERL research mission. The mission has been expanded to include the development of chemical explosive excavation technology to enable the Corps to more economically accomplish Civil Works Construction projects of intermediate size. The Project TUGBOAT was planned to provide data that could be used in the development of both chemical and nuclear excavation technology. It was also the first experiment to be conducted at the specific site of an authorized Civil Works Construction project for the purpose of providing a useful portion of the planned project.

Therefore, the objectives of Project TUGBOAT can be generally stated as (1) to provide a useful portion of the authorized Civil Works lightdraft boat harbor planned for Kawaihae Bay, Island of Hawaii, State of Hawaii; (2) to test the applicability of the cratering technique for harbor construction in a coral medium at a reasonable scale with chemical explosives; and (3) to provide technical data which can be used in the design of other chemical or nuclear explosive harbor excavations.

Project TUGBOAT extended over about a 2-yr period from the initiation of planning to the completion of a postdetonation investigation program. A site investigation program was the first on-site work and was conducted during the summer of 1969. This was followed by a series of five site calibration detonations in November of 1969. Execution of these detonations was officially designated as Phase I of Project TUGBOAT. These tests were followed by a period of data evaluation and

the subsequent reworking of the original conceptual design into the final explosive harbor design. Execution of this explosive excavation design occurred during late April and early May of 1970 and was officially designated as Phase II. During the summer of 1970, a breakwater was built to provide some protection to the excavated berthing basin. Because of a misfire and incomplete detonation of two of the charges during the execution of Phase II, a portion of the entrance channel did not meet the project criteria. A small remedial explosive excavation program was successfully executed during December of 1970 to clear the channel. This program was followed immediately by a postdetonation engineering properties technical program that extended in time through to early 1971.

MAJOR TECHNICAL PROGRAMS CONDUCTED

Many programs of a technical nature were carried out during the 2-yr period. Some were one-time programs on one or two of the three detonation phases, while others were more or less continuous throughout the period of execution of the entire project. The programs conducted during each period of field operations are briefly described in the paragraphs that follow.

Site Investigations

A site investigation program was initiated during the summer of 1969 which included geophysical surveys of the project area, hydrographic and topographic mapping, geologic investigations, wave analysis for the proposed conceptual harbor design, collection of site meteorological data, archeological explorations and mapping, an initial documentation of the fish and other marine life in the blast area, and a preliminary structural engineering survey.

Crater Measurements

Engineering surveys were conducted following the Phase I, Phase II, and remedial explosive excavation detonations by the Honolulu Engineer District to determine the crater profiles and the resulting entrance channel and harbor basin dimensions.

Seismic Motion Measurements

A comprehensive seismic motion measurement program was undertaken during both Phases I and II. The objective of the Phase I program was to provide data as a function of yield, range, and depth of burst specific to the site that was subsequently used to determine the maximum safe yield for detonations in Phase II. During Phase II, measurements were made to verify safety predictions and to provide seismic motion and structural response data as a function of range and firing

conditions. The planned firing conditions were (1) four 10-ton charges in a row fired simultaneously, (2) four 10-ton charges in a row fired sequentially, and (3) four 10-ton charges in a square array fired simultaneously. Problems occurred with the firing of items (1) and (2) which negated some of the objectives of the technical program.

The program was accomplished by personnel from the Waterways Experiment Station (WES) of the Corps of Engineers.

Structural Engineering Survey

John A. Blume & Associates, an engineering firm specializing in the effects of seismic motions on structures, was engaged to advise EERL in this vital area. The objective of the program was to assist in the determination of the maximum yield which could be safely fired during the Phase II harbor excavation detonations. The scope of the program was as follows:

1. To make an initial survey and examination of structures in the vicinity of the project site to ascertain present conditions (accomplished during site investigations.

2. To estimate the level of ground motion at which incipient architectural damage could be expected.

3. To make recommendations for changes in the planned ground motion and structural-response measurements to be made during Phase I to provide needed data.

4. To assess the results of initial survey and estimates based on the ground motion and building response recorded during Phase I, and to submit revised recommendations.

5. To resurvey structures following Phase II to determine whether any changes had occurred.

Intermediate Range Seismic Measurements

Seismic measurements were attempted by the University of Hawaii on other islands in the Hawaiian chain using instrument stations already established for a continuing earthquake study. Because of some operational difficulties, records suitable for a detailed analysis of the magnitude of motion were not obtained.

Close-in Air-Overpressure Measurements

A comprehensive program of ground level air-overpressure measurements was conducted during the execution of both Phases I and II by the Sandi- Laboratory, Albuquerque, New Mexico. The objective of the Phase I program was to provide

air-overpressure data as a function of yield, range, and depth of burst specific to the harbor site and the slurry explosive. These data were subsequently used in conjunction with other safety data to estimate the maximum safe yield for the detonations of Phase II. The objective of the program during Phase II was to verify the safety predictions and to provide data as a function of range and firing conditions. Problems encountered with the firing of the first two detonations during Phase II negated somewhat the comparison of air overpressure from a simultaneously fired row with that from a sequentially fired row of charges.

Fish and Wildlife Studies

A comprehensive program was performed by the State of Hawaii, Department of Land and Natural Resources, to determine the effects of the explosive cratering detonations on the marine environment in Kawaihae Bay. The program included:

1. A recording of the species, composition, and densities of marine life existing at the project site prior to the commencement of work by underwater transecting and photography by Scuba-equipped divers. This program was accomplished during the site investigations phase of the project.

2. A determination of the effects of the detonations in relation to the total number and/or poundage of fish and invertebrates killed or injured, the total area affected by the blast, and the distance from the blast center to which fish kills were effected.

3. A determination of the time required for and the nature of repopulation of the affected area.

Aerial Photography (Phases I and II) and Wave Measurements (Phase I)

ESSO Production Research, a division of Humble Oil Company, sponsored a program of motion picture aerial photography of the Phase I and II detonations and a wave measurement program during the Phase I detonations only. The purpose of the photography was to provide documentation of the late time crater formation process and to view the wave pattern produced by the detonations. The Phase I wave measurement program provided the first known wave data for underwater cratering detonations of significant yield

Wave Measurements (Phase II)

The Coastal Engineering Research Center (CERC) of the Corps of Engineers conducted a wave measurement program during Phase II. The program was intended to be a follow-on to the program conducted during Phase I.

Pressure, Velocity, and Acceleration Measurements in Water Surface Layers

The Lawrence Livermore Laboratory (LLL) of the University of California conducted a program to test instrumentation designed to measure shock pressure, velocity, and acceleration in the surface water layer in an underwater cratering test such as TUGBOAT. The instruments were designed to make measurements extended in time in the very high pressure and acceleration environment encountered at the Surface Ground Zero (SGZ) location.

High-Speed Photography from Ground Stations

High-speed photography of all detonations was taken from ground stations by personnel of EERL. This photography was primarily for documentary purposes.

Postshot Engineering Properties Investigations

A program of drilling and sampling in the crater area was accomplished following the remedial explosive excavation detonations in the berthing basin area and in the channel area to try to determine the extent of fracturing of the coral. Results of this program are reported here except for final results of surveys taken after 1 yr and after a major storm to determine long-term changes in the bottom conditions.

Summary of Results

Project TUGBOAT detonations were executed in three phases. Detonation yields and dates of detonation are given in Table 1. These detonations successfully produced a harbor basin and entrance channel which exceeded the design requirements in both width and depth. The detonations resulted in a channel varying in width from about 150 to 260 ft at a minimum project water depth of 12 ft. The berthing basin is almost a square area 400 ft on a side at the 12-ft water depth contour. The minimum channel design width was 120 ft and the berthing basin design requirement was a square 240 ft on a side.

The site medium is a weak coral. Tests on cores recovered in preshot drilling show a compressive strength ranging between 760 and 1738 psi, a mean bulk dry density of 1.37 g/cm^3, a mean saturated bulk specific gravity of 1.76 g/cm^3, and a mean porosity of 49%. The reef mass possesses, by an indeterminate amount, a lower mean strength, a lower mean density, and a higher mean porosity than the tests indicate.

Drilling of the charge emplacement holes during Phase I was done from a causeway which was later removed by dragline. Phase II holes were drilled from a

Table 1. TUGBOAT charge designations and yields, and detonation dates

Charge designation	Charge yield (lb)	Date of detonation	Remarks
A. Phase I			
la (Alpha)	2,000	0901 6 Nov '69	----
lb (Bravo)	2,000	1101 6 Nov '69	----
lc (Charlie)	1,975	1001 4 Nov '69	----
ld (Delta)	1,950	0901 5 Nov '69	----
le (Echo)	20,200	1101 7 Nov '69	----
B. Phase II			
II-ABCD	52,000	0916 23 Apr '60	Charges C and D did not detonate full-yield
II-EF	40,000	0901 28 Apr '70	----
II-IJKL	80,000	0901 1 May '70	----
II-GH	20,000	0901 8 May '70	Charge G deflagrated
C. Remedial Detonation			
G1, G2 C1 to C13 A1	14,800	8 Dec '70	----

jack-up floating platform. A DOW manufactured aluminized ammonium nitrate slurry blasting agent was pumped into the charge canisters after the canisters had been placed in the drilled hole and stemmed. The slurry was pumped with a truck-mounted pump through a rubber hose down a 4-in fill line that extended from the top of the canister to the surface.

Calibration tests provided information that permitted a redesign of the harbor excavation using a little more than half the original drill holes and half of the quantity of blasting agent estimated to be required in the preliminary design. The craters were broad and shallow with no lips and were actually better suited to harbor excavation in this situation than the less wide and deeper craters typical of dry land cratering detonations. The cratering mechanism appears to be one of densification of the coral through crushing and subsequent settling. Aerial photography showed that the crater remains devoid of water for several seconds after detonation and then is filled by coral and water as the crater walls fail into the crater. Wave staffs that were placed in the coral near the craters moved toward the crater before being overrun by the outrunning water wave (further evidence of this failure process).

The 10-ton Echo crater had a radius to the 12-ft depth contour of about 60 ft. This parameter was used to design the harbor detonations. Spacing between charges was set at two times this number.

Low-order detonation of Charges II-C and II-D and the deflagration of Charge II-G apparently was due to inadequate boostering. These misfires made it necessary to do some small remedial detonations which were successful in clearing the channel.

The final channel surface is flat, level and sandy, with scattered small coral blocks lying on it. Foundation conditions in the channel are similar to those in medium to dense sand. A short distance outside the channel, natural coral conditions exist. The material in the channel is more homogeneous than that of the natural coral reef. In the berthing basin area, a layer of soft mud from 2- to 9-ft thick lies at the surface. This layer is not present in the outer part of the channel.

Crater zones were not satisfactorily defined by the drilling program. They were crudely defined by the acoustic profiling surveys; the true crater by the limit of dipping beds within the crater, and the rupture zone by the limit of the basalt reflection. To define the true crater specifically by drilling would be very difficult.

A long-term settling effect in both the channel and the surrounding natural coral was detected by surveys taken during May and December 1970. On the average the surface was lowered during this 7-mo period by 1 or 2 ft. This effect supports results of the acoustic profiling, which indicate that the natural coral was shattered by the blasts to large distances out from and below the cratered channel.

The photography taken in the wave measurement programs aided in an understanding of the crater formation process and showed the wave patterns generated by the detonations to be very complex. The wave of maximum height was found usually to be the first wave of the explosively generated system, and it is characterized by a high crest followed by a long, shallow trough. The maximum wave height generated was during the II-EF detonation and was about 11 ft in height at the closest point of measurement (230 ft). Scaling relationships were developed for predicting wave height and travel time.

The programs to determine the effect of the detonations on the marine environment were very comprehensive. The marine life at selected locations was observed and recorded during and following the major detonations. The distances from the detonations to which fish kills and injuries were effected were determined by the anchored fish cage technique. Also, the dead and stunned fish were picked up immediately following each detonation; then they were studied and

recorded.

A total of 111 different species representing 34 families of marine fishes was found at the project site through underwater observations by divers and through collections of dead and injured fishes after the detonations. Of the 76 species that were recorded by the divers, 37 were not found during postdetonation collections, and conversely, 35 of the 74 species found during postdetonation collection activities were not observed during the underwater observations. These discrepancies were attributed to the limitations inherent in the observation and collection methods that were employed.

For the large detonations of Phase II, the distances to which all fish in fish cages were killed were 100 ft for detonation II-ABCD, 120 ft for detonation II-IJKL, and 210 ft for detonation II-EF. The maximum distance to which any fish were killed or injured probably did not exceed 300 ft on any of the three detonations.

As estimated from the collections made following the detonations, the families of fishes most affected within the area of dead and injured fish were squirrelfish, butterfly fish, damselfish, surgeonfish, cardinal fish, and the puffer. Not all fishes collected following the detonations were dead. Some were just stunned. As a test, a live but stunned fish that was picked up was kept in a tank for several weeks and appeared to be in good health at the end of that time. The observation data indicate that segments of the project site still containing coral (i.e., immediately adjacent to the blasted channel and berthing basin) are being rapidly repopulated from adjacent unaffected areas. These observations also show that the detonations altered the immediate areas of the channel and berthing basin from one of clear water and hard, coral bottoms to one containing a silt bottom and murky waters similar to those found at the Phase I detonation site prior to the blasts. It is suspected that the final species composition and density in these areas will reflect the changes that were incurred to the habitat.

Instrumented ground-motion seismic stations in the vicinity of Project TUGBOAT were observed to respond in a fairly uniform manner. Maximum peak particle velocities recorded during the 1-ton events ranged from about 1.5 cm/sec at a distance of about 1500 ft to about 0.1 cm/sec at a distance of 8200 ft. Data recorded during the 10-ton detonation ranged from about 4 cm/sec at a distance of 1800 ft to about 0.4 cm/sec at a distance of 8000 ft. Finally, 40-ton amplitudes diminished from about 6 cm/sec at a distance of 2600 ft to about 0.8 cm/sec at a distance of 7600 ft. No reliable seismic amplitude dependence upon depth of burst could be established. Two yield scaling methods verified one another in defining

a yield scaling factor of about $W^{0.52}$. The II-EF sequential detonation produced measurably lower ground motions than the expected motion for simultaneous detonation of the same charges.

Predictions of building response to the TUGBOAT detonations identified the Ultramar Warehouse to be the critical structure from an architectural damage standpoint. Detonations during Phase II were limited to 40 tons to minimize the possibility of any damage. No damage claims were filed as a result of any of the detonations.

Positive peak airblast overpressures and positive phase impulse from the TUGBOAT Phase I explosions were about five times those predicted on the basis of measurements made from cratering explosions in soil. Peak overpressures estimated by applying multiple-charge overpressure amplification factors to the Echo detonation results were small enough that the possibility of blast damage on the Phase II detonations was expected to be acceptable.

Peak overpressures for Detonation II-ABCD, II-EF, and II-IJKL multiple-charge Phase II detonations were approximately 1, 1.4, and 2.5 times that for a single-charge detonation having a yield equal to one of the charges in the multiple-charge array. Positive impulses were about 2, 2, and 4 times that for a comparable single charge. These data indicate that in Detonation II-ABCD, Charges II-C and II-D contributed very little to the positive phase impulse observed. The data pertaining to the reduction of overpressure from the delay of successive charge detonations in a row were not adequate to draw more definite conclusions.

No glass was broken and the estimates of probability of breakage based on maximum measured peak overpressures was never greater than 5 panes per thousand.

Charge II-D SGZ area was instrumented for pressure, velocity, and acceleration measurements in the water. Peak velocities of 66 and 61 ft/sec were measured by the subsurface and surface gages, respectively. Peak accelerations were 356 and 311 g, respectively. The subsurface pressure gage measured 414 psi. The II-IJKL detonation was also instrumented, but accelerations were nearly double the design limit of the gage canisters. These accelerations resulted in early destruction of the canisters and the loss of considerable data. Peak accelerations of 2780 g and pressures of 2513 psi were recorded. The experience was very useful in developing LLL's capability to instrument surface water environments. It was fortuitous for this program that Charge II-D did not go full-yield as much more information was obtained about the overall capabilities of the instrumentation.

REFERENCE

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ENVIRONMENTAL IMPACT OF SUNKEN TARGET HULLS

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During the past five years, the Naval Undersea Center (NUC) has sunk seven surplus ships off California's San Clemente Island as part of weapon evaluations. San Clemente Island is owned and operated by the Navy and is approximately 40 miles from Long Beach and 70 miles from San Diego. The nearest land-based activity is on Catalina Island, about 20 miles away. San Clemente Island is an excellent location for environmental studies because of its remoteness and relatively pristine conditions. The lush marine environment is very similar to the Southern California coastline as it appeared before the onslaught of man and pollution. The sunken hulls range in depth from 0 feet to 1500 feet and have provided unique opportunities to study the effects on sea floor ecology elicited by the intrusion of these substantial hulks. An understanding of the change in ecology may be of value in several areas: evaluating the environmental impact of deep-ocean ordnance dumping, performing rescue or salvage operations on sunken ships, studying the effects of nuisance animals on undersea habitats, or simply locating sunken ships. The objective of this program was to survey the ocean bottom in the area before and after sinking these "environmentally clean" target hulls and interpret any changes in ecological parameters and animal distribution patterns. "Environmentally clean" refers to the Department of the Navy Final Environmental Impact Statement on use of Target Ship-Hulls in Exercises at Sea, which defines procedures for removing residual petroleum, floatable contaminants, and generally cleansing the hull.

Since animal attraction to artificial reefs has been documented and well demonstrated in a variety of locations, it was expected that marine life would aggregate on and around all of the hulls. The artificial reef has become increasingly important during the last 10 years and has produced many prolific marine communities. Different organizations in nations throughout the world have established these reefs off their coasts by using automobile bodies, old streetcars, car and truck tires, large-diameter clay and concrete pipes, hollow concrete blocks, oyster shells, and even toilet bowls. The results have often been dramatic and nearly always successful in establishing productive communities similar to the diverse and abundant biota supported by natural reef habitats. Thriving communities exist around natural and man-made reefs because they provide protection, food, and/or attachment sites. In certain situations schools of fish have moved into an area within a few hours of artificial reef placement, and in others the fish population has increased around the new reef by 300% within a few years. However, not only fishes have been attracted. They are directly or indirectly supported, at least in part, by other plant and animal species that have also become an integral part of the reef community food chain. Certain animals might initially come to the reef for a protected hiding place, but they would not remain there if the food supply were inadequate. Food is provided from within the community itself, from surrounding communities, or a combination of both. In addition to increased productivity, the aggregated distribution within the reef increases the probability of mating and reproduction to maintain the reef population.

Most ecological studies of natural and man-made reefs have been in water of 100 feet or less since the SCUBA equipment commonly used in reef surveys is most effective in shallow

water. Natural reef-like substrates include coral reefs, kelp beds, and rock configurations. Generally in temperate coastal zones, 100 feet is also the lower limit for kelp beds and other natural reefs with attached algae since adequate sunlight for photosynthesis and development does not penetrate much below this depth in turbid coastal waters. Many natural reefs do occur at much greater depths where algae may or may not be present. In clear tropical waters, coral-reef building occurs down to 150 feet, although most larger reefs are found above 100 feet. Having a virtual transect line of artificial reefs in the form of sunken hulls from the intertidal zone down to a depth of 1500 feet will provide valuable information to help interpret the attractive power of artificial reefs at various depths and the processes that are involved in establishing new communities at those depths. The hulls below 150 feet become even more significant when considering that artificial reef effects at those depths are virtually unknown. Although not all the hulls off San Clemente have been surveyed, they will all be discussed in order of increasing depth (Fig. 1).

The ex-GREGORY, a surplus destroyer, was actually not sunk but went aground during a storm in March 1971 after being moored on the seaward side of San Clemente Island for use as a target hull. Since that time it has been used as a target several times in the testing of various projectiles and missiles. The ex-GREGORY, in place for over two years now, provides a good site for evaluating the environmental impact of shore bombardment in a localized area. At this time, however, not enough data are available for analysis since the site has only been observed on a cursory basis.

The ex-BUTLER, a decommissioned destroyer escort, sank off the northern end of San Clemente Island in December 1971, but this too was unplanned. The ex-BUTLER had been used as a target for two experimental warheads and was moored when a storm broke off the stern section, which sank immediately in 75 feet of water. Later, the bow portion was loaded with 400 pounds of Composition C-4, which is 91% RDX, and was being towed out to sea for deep-water dumping when it accidentally sank to a depth of 800 feet. Due to the bizarre nature of the sinking, no pre-sinking surveys were conducted. As the areas around the stern are shallow enough, animal distribution patterns are fairly well known. In this case, at 75 feet, it is clear that the artificial reef effect is in operation. Diver surveys have revealed that schooling fishes had moved into the area in less than one month after sinking. Later surveys have confirmed that there are still more fish in the area around the sunken hull. As far as the environmental impact is concerned, the increase in the local fish population indicates that the gross effect is a good one. The bow section at 800 feet has not yet been investigated. It is the only hull at San Clemente Island that still has explosives on it. No conclusions can be drawn regarding detrimental effects to the marine environment since a detailed survey has not been conducted. In addition, the quantity of explosives is small and still deep within the keel of the ship.

The ex-MORAY was sunk in 150 feet of water on the coastal side of San Clemente Island in June 1970 by two Torpedo Mk 46 warheads. It was observed and photographed a month after sinking, and a second survey was made in September of the same year. The third survey was conducted in April 1971. The complete photographic survey totals about 1500 pictures. Many fishes had apparently been attracted to the submarine on the bottom less than one month after sinking, as was the case with the ex-BUTLER at 75 feet. No surveys were conducted before the ex-MORAY sinking either, but attraction was evident when the number of fish around the submarine was compared to the number in nearby areas at the same depth.

The Navy's Cable-Controlled Underwater Research Vehicle (CURV), an unmanned submersible, was used to survey sunken hull sites below 125 feet. Its television cameras were monitored on the surface, and its 35 mm camera on the bottom provided a photographic record for data analysis. Analysis includes only those species photographically visible.

During post-air ing surveys, as the CURV moved along the bottom and approached the ex-MORAY on the bottom, actual photography commenced at a distance of approximately 100 feet, with few fish observed in the monitor or in later analysis of the photographs. As soon as the sub became visible at a distance of about 15 feet, hundreds of fish could be seen. Since they were the most mobile animals in the area, one would expect fish to be the first inhabitants of the new reef. Surveys three months and nine months after sinking revealed even more fish than the first survey. More fish were observed in photographs from the last survey than any other, indicating an increase in the local fish population with time. Fishes most common in the area of the submarine and apparently using it for shelter were the blacksmith (*Chromis punctipinnis*), sheephead (*Pimelometopon pulchrum*), rockfish (*Sebastes* sp.), and perch (*Embiotica* sp.) (Figs. 2 and 3).

The ex-MORAY rests on a sandy bottom with few rock outcrops. A hydroid-bryozoan community carpets the ocean floor in this and surrounding areas. Numerous mussels were also observed in certain patches on the bottom, but it is believed this population was extraneous, since *Mytilus* sp. is usually found only at much shallower depths. Clumps of these mussels were either dislodged from higher zones and came cascading down or were knocked off the hull of the submarine during sinking or after hitting the bottom. Many empty mussel shells were also observed. These animals may have been killed and removed by the explosion during sinking, after bottom impact, or after consumption by sea stars. Photographs did show sea stars (*Patiria miniata* and *Pycnopodia helianthoides*) actively feeding on these mussels. One picture reveals a sea star feeding on mussels still attached to the submarine. There was little evidence that animals had attached themselves to the sub after sinking and nothing to indicate that the more mobile invertebrates were aggregating on and around the submarine in substantial numbers. Most evident were the sea stars feeding on the mussels, but these were probably not attracted by the sub itself, but rather by the mussels. Since this particular artificial reef had been in place for less than one year, there may not have been enough time for other invertebrates to move into the area.

The ex-HOPEWELL, an inactive destroyer, sank in February of 1972 after sustaining damage from an air-to-surface missile, the WALLEYE. The hull rests on the bottom in 400 feet of water on the seaward side of San Clemente Island. It was surveyed for the first and only time in May of 1972, three months after sinking. After only one photographic survey with CURV, the data necessary to explain any artificial reef effects are inadequate. Photographs revealed that a few different species of fish (flatfish, cod, rockfish) and one crab were apparently remaining close to the destroyer, but it was probably too early to draw any conclusions. Large numbers of schooling fishes were definitely not present, as was the case with the ex-BUTLER and the ex-MORAY.

The ex-VAMMEN, an inactive destroyer escort, is on the bottom in 600 feet of water. It sank in February 1971 after sustaining damage from a CONDOR missile that was launched from an aircraft. It was moored at the time on the seaward side of San Clemente Island. The ex-McNULTY was used as a destroyer escort test hull for a fuel-air explosive (FAE)

weapon system It too was a stationary test for assessment of damage produced by two charges of about 1000 pounds each. After the test in November 1972, it was towed to a pre-determined location, where it now rests on the bottom in approximately 1000 feet of water on the coastal side of San Clemente Island. Neither of these hulls has been surveyed.

The ship that has received the most attention is a surplus fleet submarine, the ex-BURRFISH. Three detailed pre-sinking surveys were conducted in the proposed sinking area, with a total of about 1500 photographs of the undisturbed bottom. The ex-BURRFISH was sunk on the seaward side of San Clemente Island in November 1969 while running on the surface by remote control. The ordnance used in this test was a Torpedo Mk 46 launched by helicopter. The first post-sinking survey of the ex-BURRFISH came in December 1969. Surveys were later conducted in January and June 1970 and June 1971. Over 3000 photographs have been taken of the area since the submarine went down.

Pre-sinking photos of the area revealed a sea floor of soft sand and mud with a gentle slope and very few rock outcrops. Echinoderms dominated the observed bottom community. In order of decreasing abundance, they consisted of heart urchins (probably *Brisaster* sp. or *Brissopsis* sp.), pink sea urchins (*Allocentrotus fragilis*), and unidentified species of sea anemones, sea cucumbers, sea stars, glass sponges, fish, and crabs (Fig. 4). Although echinoderms made up about seventy percent of the epibenthic macrofauna, they probably constituted only four or five percent of the total biomass. There may have been enormous numbers of sediment-dwelling animals (infauna), such as polychaete worms, not exposed to the camera and exposed animals too small to show up in a photograph. As with the ex-MORAY, this analysis by necessity only includes those macroscopic animals normally exposed on the bottom surface.

Although burrowing heart urchins were clearly the most abundant animal in all preliminary surveys, the particular site where the submarine actually touched bottom was dominated by the pink sea urchin. Further, this site was more sparsely populated than many areas previously surveyed. It should be easier, therefore, to document any influx of marine life. Because of depth differences, one would not expect the same type of community to be established around all of the hulls. There were not as many fish on the bottom at 1500 feet around San Clemente Island as there were above 200 feet, and they did not exhibit similar schooling behaviors.

As of the last survey, twenty months after the ex-BURRFISH was sunk, the two species apparently attracted to the submarine were lithodid crabs (*Paralomis* sp.) and aspidochirote sea cucumbers (possibly *Parastichopus* sp.). The preliminary surveys revealed only one or two of these crabs, but at least six have been photographed in the immediate vicinity of the submarine, in most cases on or around the sub or debris from it (Fig. 5). The sea cucumbers were quite numerous in preliminary surveys but were not gathered together in the same clumped distribution pattern now found within 15 feet of the ex-BURRFISH (Fig. 6). The same is true for the few fishes that were observed. They were found in some cases clustered in groups of two or three on and around parts of the submarine.

In summary, influx of marine life in the area of the ex-BUTLER at 75 feet and the ex-MORAY at 150 feet has been much more rapid and dramatic than in the area of the ex-HOPEWELL at 400 feet and the ex-BURRFISH at 1500 feet. This is due in part to the

mobility and numbers of fish in the area. From the photographs, it does not appear that any larger mobile invertebrates have entered the first three sites, except sea stars moving in to feed on mussels in the area of the ex-MORAY. At the ex-HOPEWELL and ex-BURRFISH sites, movements of fishes have not been very pronounced, although some species were closer together and slightly more numerous around these hulls than in other nearby areas. The most significant changes in the area of the ex-BURRFISH were the concentration of the local crab population around the submarine, apparently seeking a protected home, and the comparatively large clusters of sea cucumbers.

These studies are only beginning. Baseline data are being gathered. It will probably take years for complete ecological progression to fill all available niches in hull areas. It does appear at this point that any environmental impact around "environmentally clean" hulls that have been sunk will be beneficial and lead to an enhancement of bottom flora and fauna. Community development around the ex-BUTLER at 75 feet and the ex-MORAY at 150 feet has occurred much more rapidly than development of the ex-HOPEWELL at 400 feet and the ex-BURRFISH at 1500 feet. The same will probably be true for the hulls below 200 feet that have not yet been examined, the ex-VAMMEN (600 feet) and the ex-McNULTY (1000 feet). Ecological development generally appeared slower at the greater depths and it probably takes longer for all changes to emerge and establish the reef community food chain. Once the information is available, however, we can better evaluate the ecological impact of deep dumping sites used for unwanted ordnance since we will know what would happen around an "environmentally clean" hull on the bottom. It will also aid in the selection of potential dump sites, should they be required, or suggest that other techniques be used for disposal.

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FIG. 1 SUNKEN HULL MAP

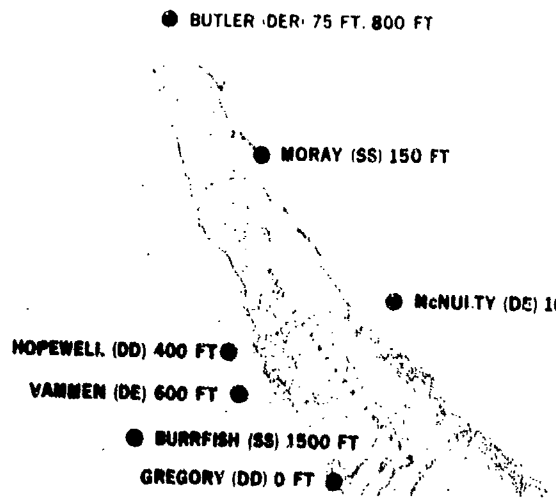

FIG. 2 FISHES IN RESIDENCE AROUND EX-MORAY AT 150 FEET AFTER 9 MONTHS

FIG. 3 LARGE NUMBERS OF SCHOOLING FISH IN THE IMMEDIATE VICINITY OF EX-MORAY

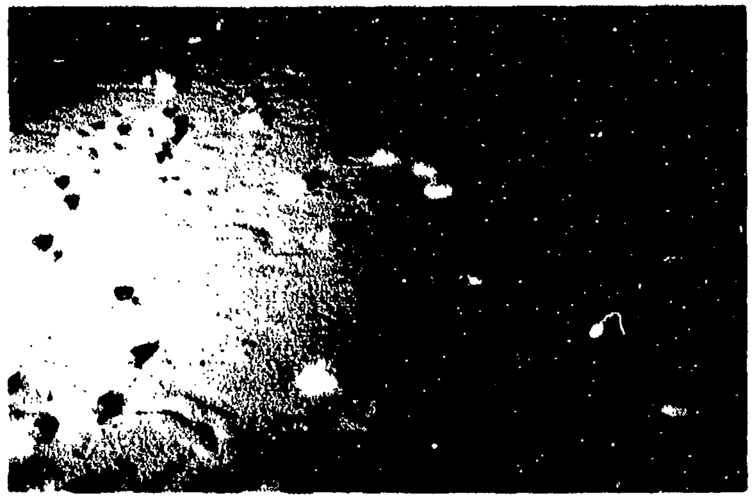

FIG. 4 BOTTOM AT 1500 FEET BEFORE SINKING OF EX-BURRFISH

FIG. 5 CRAB AND AGGREGATION OF SEA CUCUMBERS NEAR EX-BURRFISH

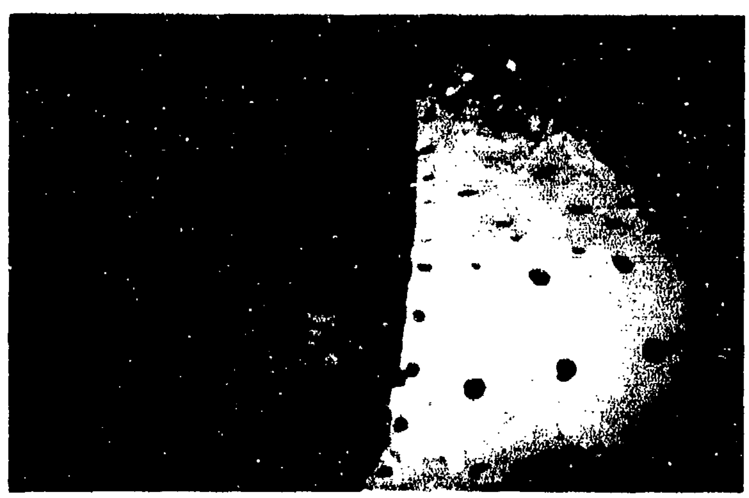

FIG. 6 CRAB ON DETACHED PIECE OF EX-BURRFISH AT 1500 FEET

SOME ASPECTS OF UNDERWATER EXPLOSIONS AND MUNITIONS DISPOSALS

R.B. Bridge, E.C. Czul, & J.J. Gennari

It is now ten years since the implosion of THRESHER off the coast of New England. To avoid future disasters such as this a search to determine its cause was conducted with equipment immediately available. The Ocean Engineering Branch of the Naval Research Laboratory had cameras capable of operating at that depth and after more than a year succeeded in photographing the major portions of the wreckage. Side-looking sonar and magnetometer signals had been multiplexed with the camera commands allowing a simultaneous search with all sensors and an acoustic underwater tracking system had been developed. Substantially the same equipment was used in the search for the nuclear munitions immersed off Spain and again for the imploded submarine SCORPION in 1968. The research submersible ALVIN was located with it as was the French submarine EURYDICE.

Since 1970 our efforts have been directed toward assessing the environmental impact of munitions disposals. Surveys have been conducted of the scuttled chemical munitions ship, LEBARON RUSSELL BRIGGS, at Deep Water Dump Area F, the MONAHAN site (Area E), and Area A where four ships were sunk.

Meaningful assessment of the effects of these operations requires a survey prior to the event and several post dump surveys to measure the decay of the effects. Further, to measure the gradient in the horizontal plane of various parameters near the dump site requires navigation two orders of magnitude more precise than does normal oceanography. This is provided by the Underwater Tracking Equipment aboard USNS MIZAR (T-AGOR-11), the vessel normally used by NRL to conduct these surveys.

A charitable comparison of the logbook positions for the five ships sunk off Cape Flattery in Area G with the actual locations as measured by Spiess gives an rms error of 3.3 miles. These were operational Loran A results achieved in an area where the theoretical accuracy is less than one nautical mile. The two escort vessels of the BRIGGS reported a difference in the sink position of 2.1 miles even with an increased awareness of the need for accuracy and the use of Loran C. The theoretical repeatability here was less than 0.1 mile. Experiences at Areas A and E have been similar or worse. Satellite navigation may give accuracies of 0.1 mile, but to reach this requires auxilary equipment not available on MIZAR or similar ships. Typical operational errors are $\pm$ 0.5 mile. Acoustic beacons and the Underwater Tracking Equipment give errors of one percent of the water depth in a local frame of reference. Repeated satellite fixes can then locate this frame of reference geodetically.

With an average disposal costing $50,000, an environmental impact statement priced about the same, and a survey of one square mile to a 95% search effectiveness costing a similar amount, one can make a trade off as to the value of navigation equipment. These numbers also allow a comparison with alternate methods of disposal.

Figure one shows the MIZAR, a 3800 ton converted cargo ship with a vertical well thru its center. Figure two shows the search fish being lowered thru the well securely restrained by the carriage as it crosses the air-water interface. The Underwater Tracking Equipment is shown pictorially in Figure three and a typical computer print-out in Figure four. A Side Looking Sonar recording is Figure Five. Wide and normal angle photographs from the SCORPION search are shown in Figure six. A photographically monitored trawl with specimens collected by it is shown in

Figure seven. Finally, Figure eight is a photograph of the coffins containing the nerve gas rockets in the hold of the LEBARON RUSSELL BRIGGS. This was taken in 16,000 feet of water.

In conclusion, whether you decide to dump or detonate, we recommend that you make a predisposal survey; use the best navigation that you can afford; and put down acoustic beacons or transponders. Whether or not you plan for the hulk to remain intact, paint it to aid in optical detection and photo analysis, and please, remove any rigging that might ensnare our sensors.

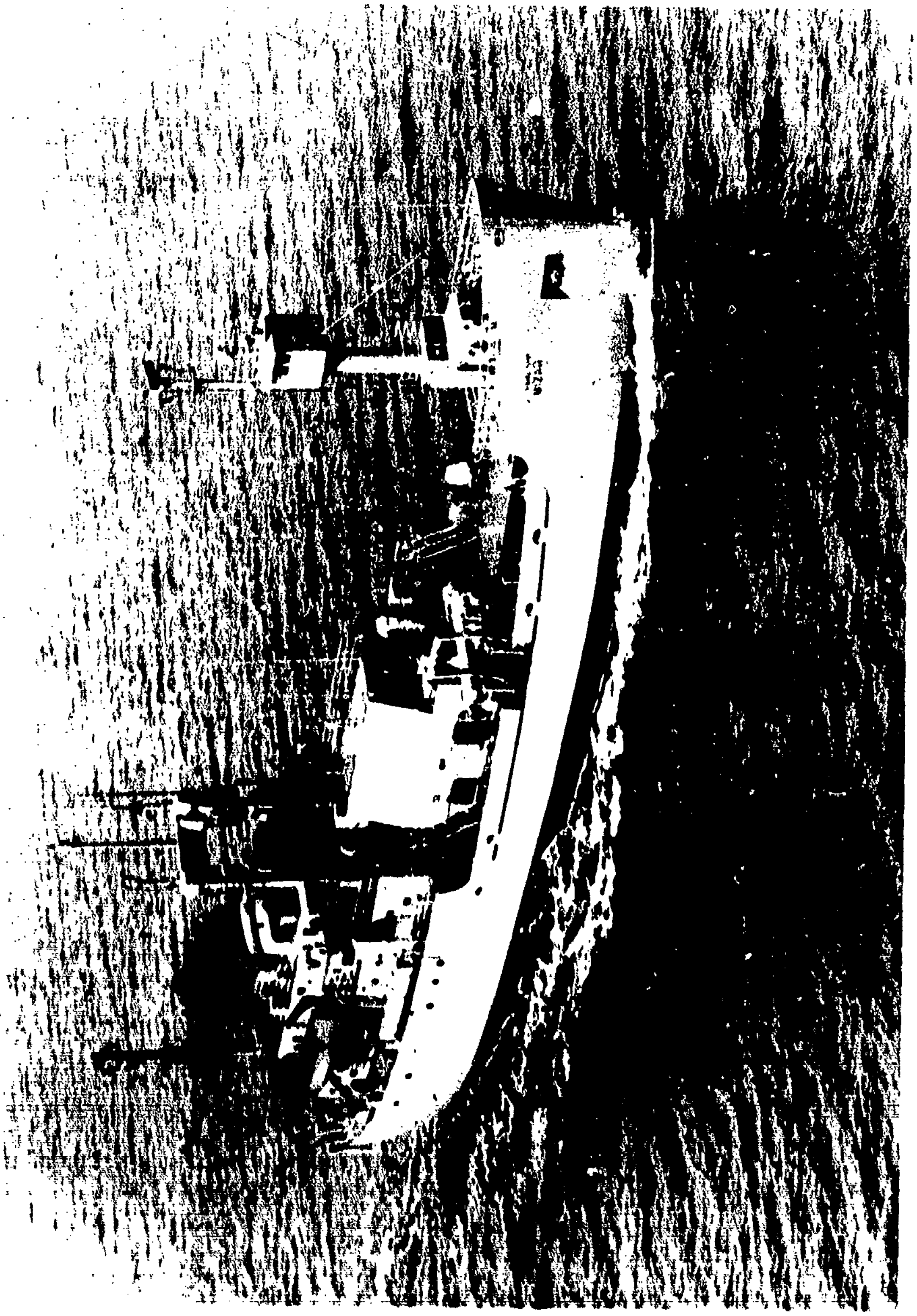

FIG. 1 USNS MIZAR T-AGOR-11

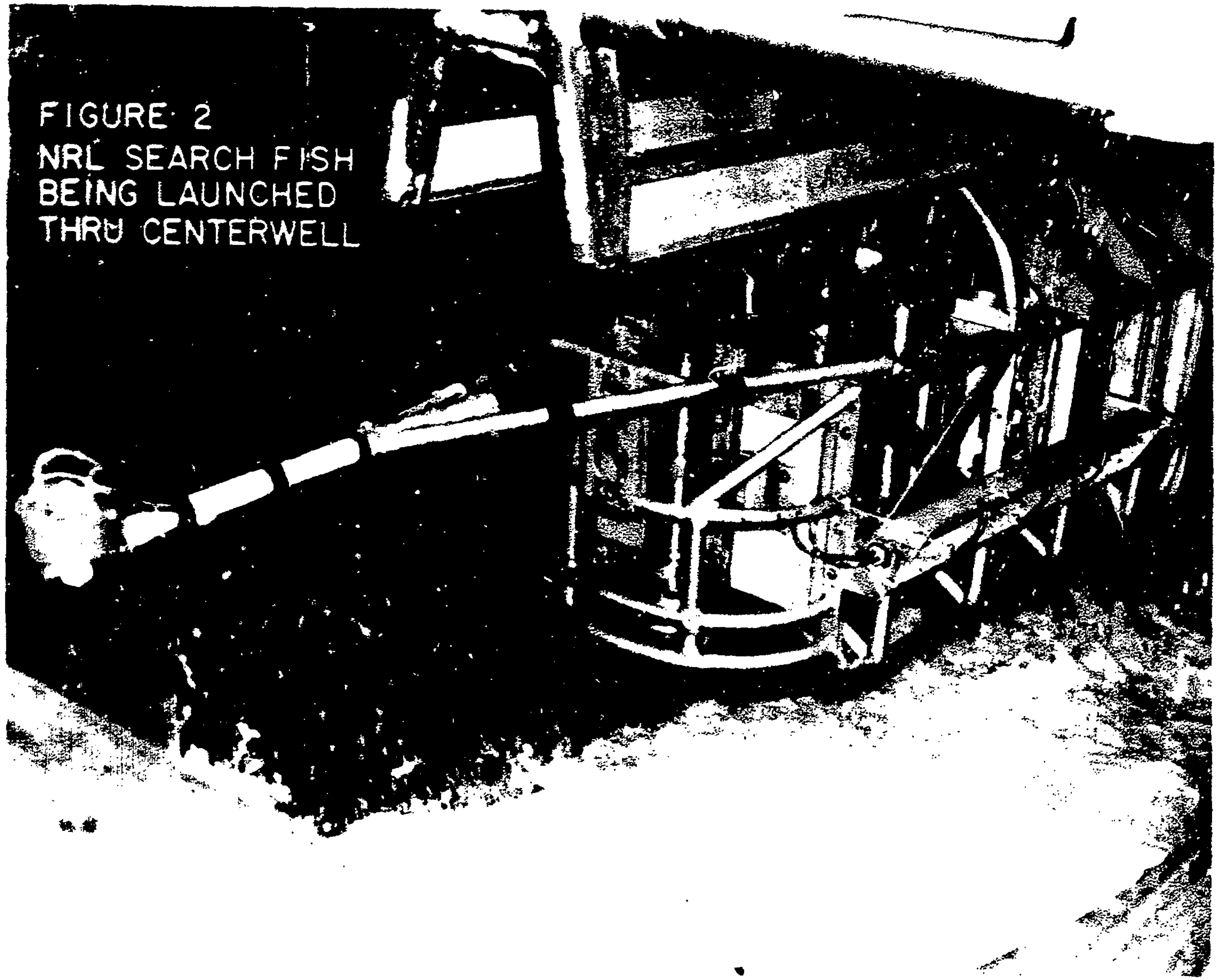

FIG. 2 NRL SEARCH FISH BEING LAUNCHED THRU CENTERWELL

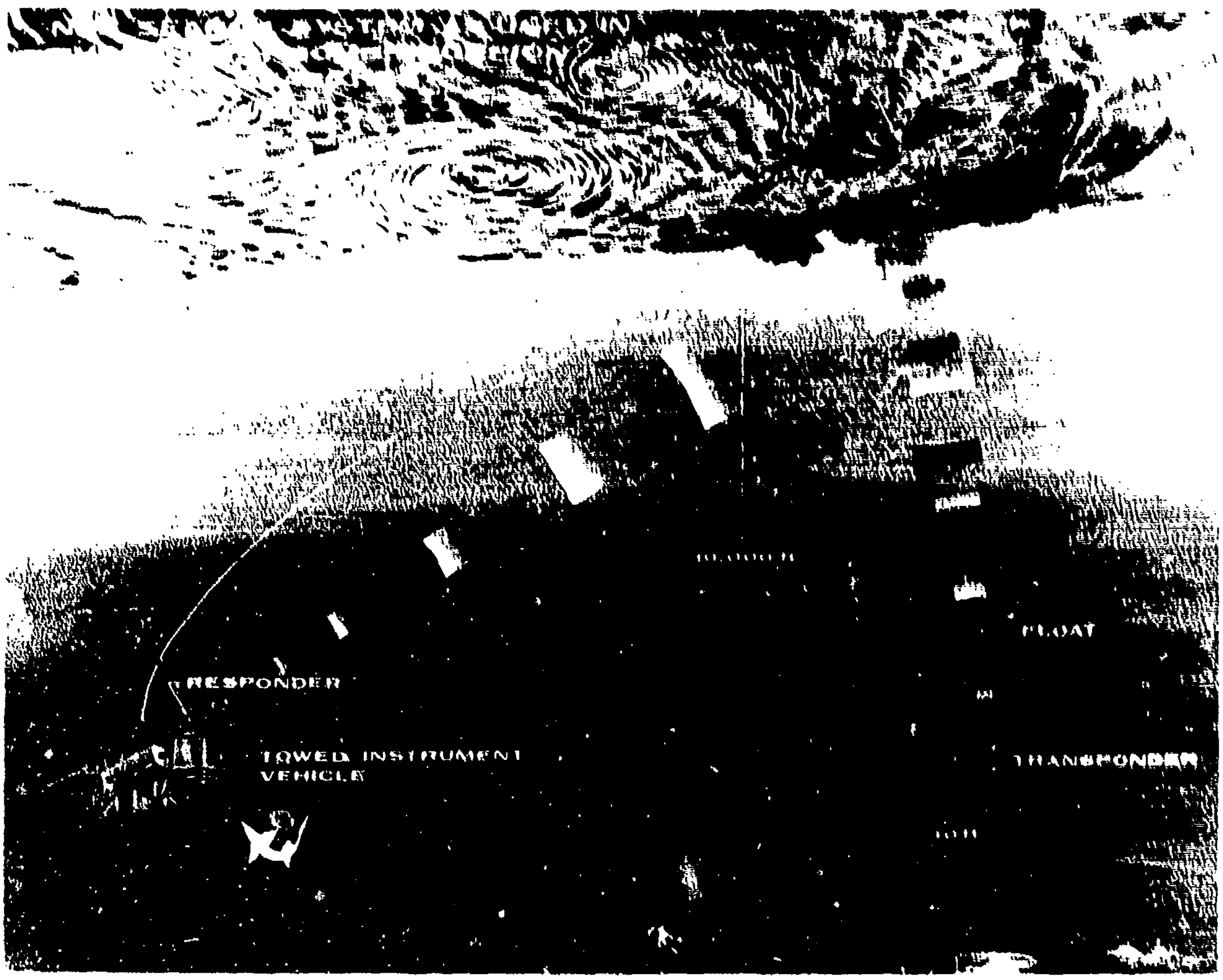

FIG. 3 NRL SEARCH SYSTEM AS USED IN THRESHER, H-BOMB, SCORPION, AND ALVIN SEARCHES

10/12/71
DWD IX RUN NO. 7
SOUND SPEED = 4950.
1. R = RESPONDER

TIME	DIST(N-S)	DIST(E-W)	DEPTH	IDEN	HEADING
10:49:43	2402 S	2549 E	7453	R	251
10:48: 3	2464 S	2549 E	0	R	S
10:50: 6	2271 S	2523 E	7502	R	250
10:48:27	2432 S	2558 E	0	R	S
10:50:30	2474 S	2577 E	7410	R	249
10:48:50	2415 S	2521 E	0	R	S
10:50:53	2331 S	2560 E	7451	R	246
10:49:13	2397 S	2594 E	0	R	S
10:51:16	2370 S	2544 E	7436	R	245
10:49:43	2381 S	2529 E	0	R	S
10:51:39	2293 S	2651 E	7416	R	245
10:50: 6	2372 S	2533 E	0	R	S
10:52: 3	2231 S	2575 E	7446	R	245
10:50:30	2367 S	2557 E	0	R	S
10:52:26	2202 S	2585 E	7441	R	247
10:50:53	2352 S	2565 E	0	R	S

"S" DENOTES SMOOTHED VALUE FOR FIVE POINTS

FIG. 4 TYPICAL PRINTOUT OF NRL UNDERWATER NAVIGATION EQUIPMENT

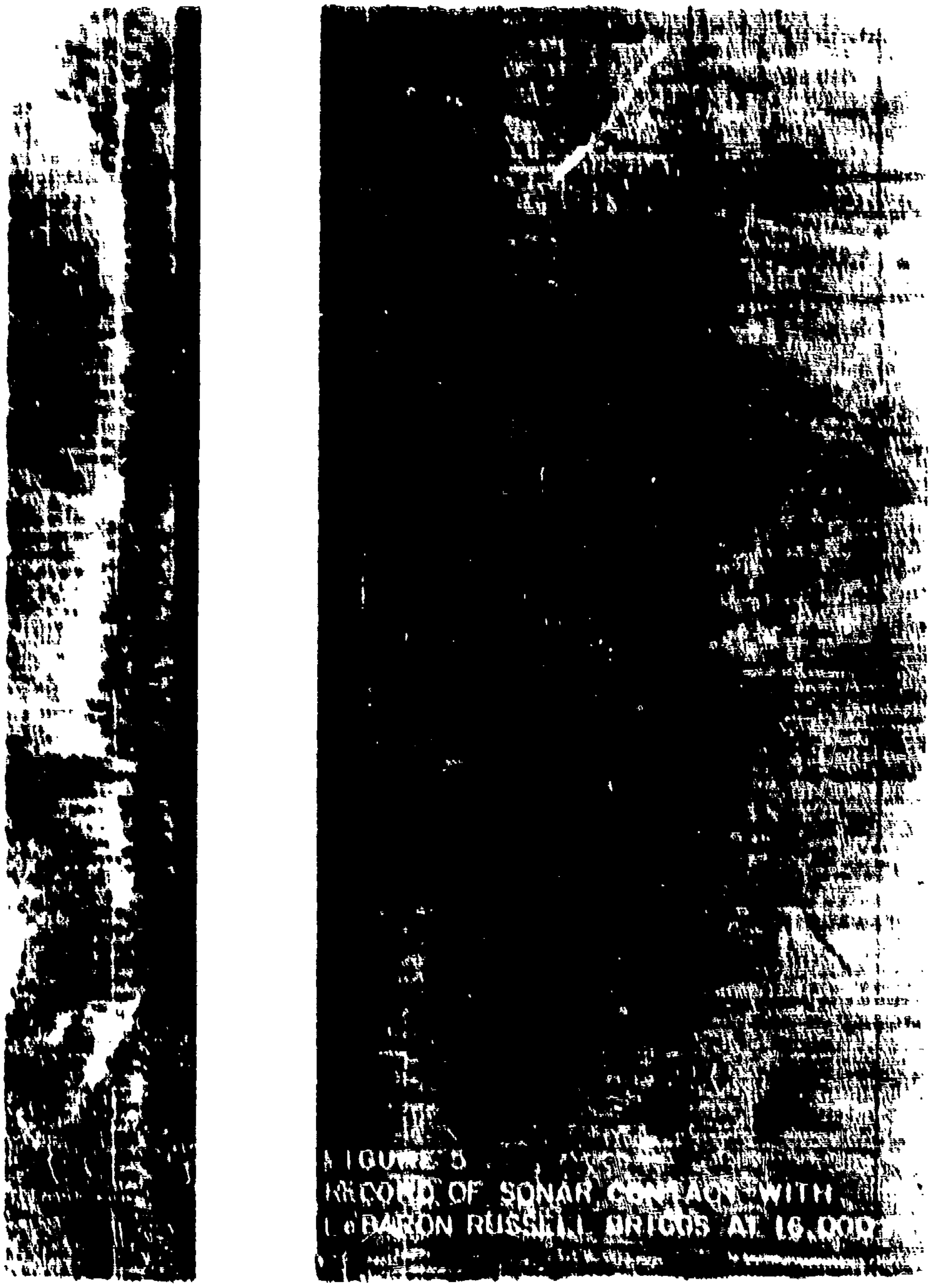

FIG. 5 RECORD OF SONAR CONTACT WITH LEBARON RUSSELL BRIGGS AT 16,000 FEET

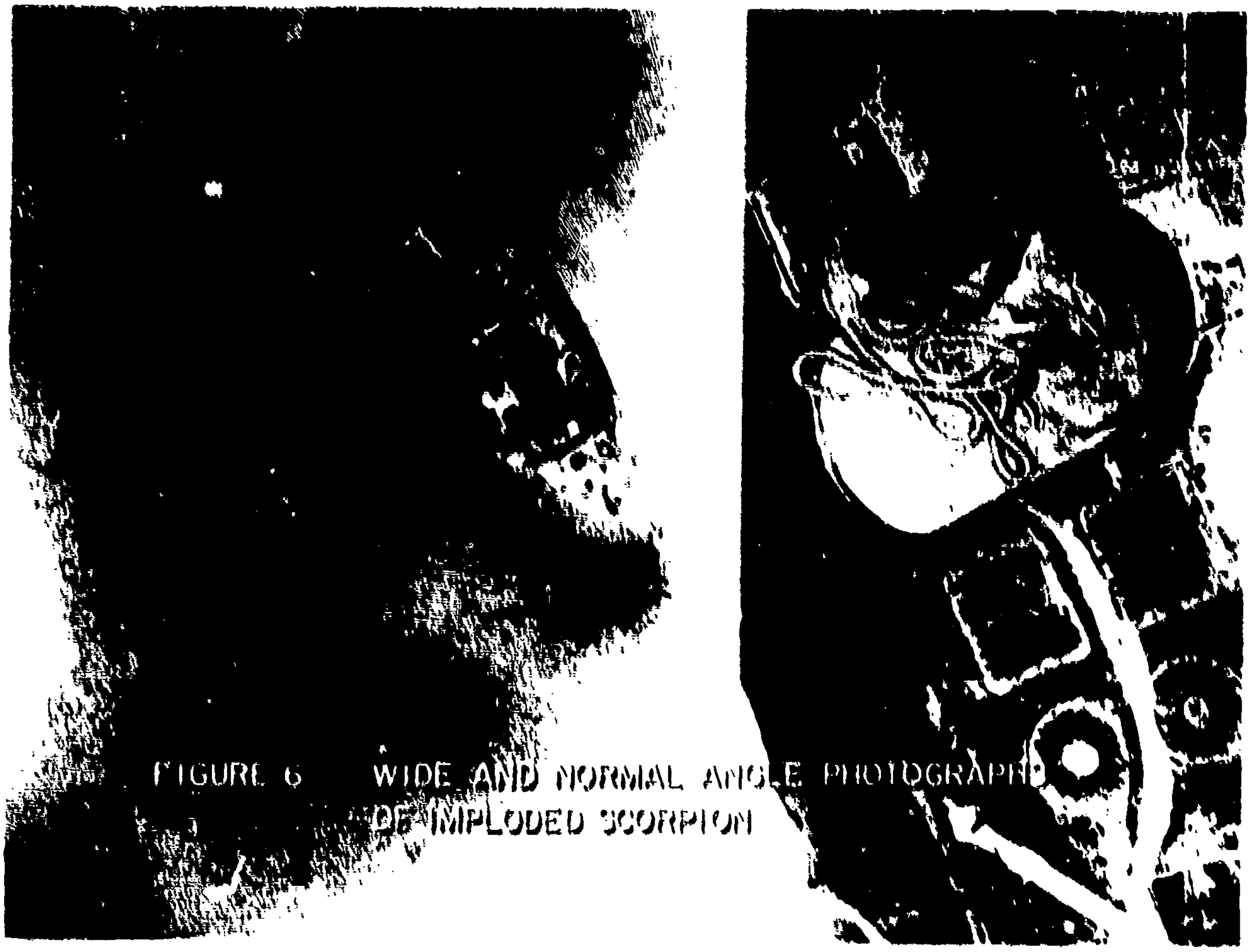

FIG. 6 WIDE AND NORMAL ANGLE PHOTOGRAPHS OF IMPLODED SCORPION

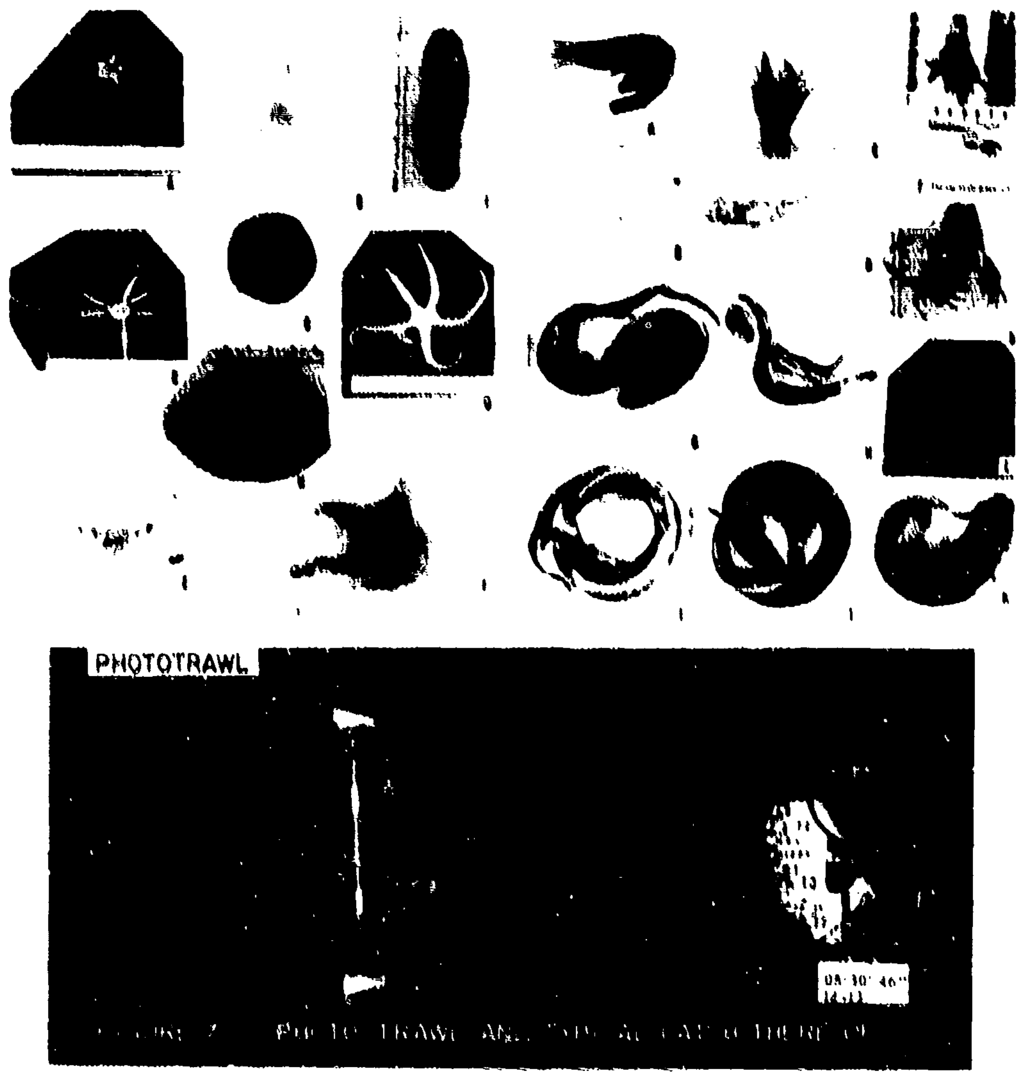

FIG. 7 PHOTO-TRAWL AND TYPICAL CATCH THERE OF.

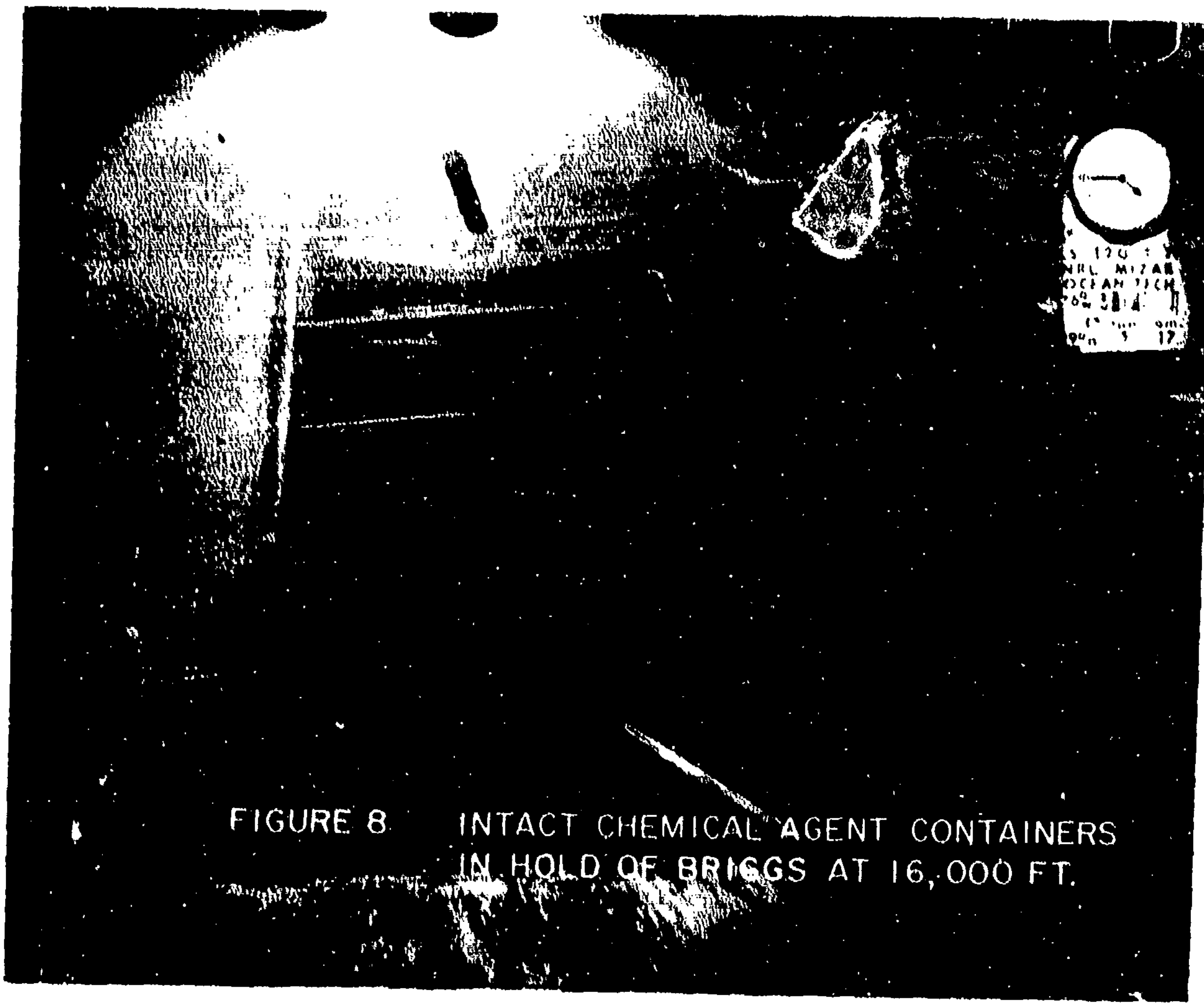

FIG. 8 INTACT CHEMICAL AGENT CONTAINERS IN HOLD OF BRIGGS AT 16,000 FEET

DEEP WATER DUMP AREA A: CHEMICAL AND BIOLOGICAL CONSIDERATIONS

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ABSTRACT

Between June 1967 and June 1970, four surplus World War II cargo ships were scuttled in the Atlantic in Deep Water Dump (DWD) Area A, approximately 150 miles east-southeast of New York City. The ships carried cargos of unserviceable chemical nerve agent munitions and obsolete conventional munitions. A preliminary survey of the environmental conditions in the vicinity of the sunken hulks was carried out by Naval Research Laboratory personnel aboard the research vessel USNS MIZAR in 1969. This survey was followed by a much more detailed investigation conducted by NRL with participation by Florida State University, Edgewood Arsenal, the Naval Weapons Laboratory, and the Naval Oceanographic Office. During the 1972 survey, two hulks--DWD VIII and XI--were located on the bottom in DWD Area A and were identified in photographs. A debris field which resulted from the detonation of DWD XXI was also located and photographed, but repeated attempts to locate debris from the detonation of DWD XII failed. An extensive environmental sampling program was carried out near the still-intact hulks of DWD VIII and XI. The results of the chemical survey, in which water samples from the immediate vicinity of the hulks were analyzed, show no detectable leakage of chemical munition products into the surrounding water. A detailed marine-biology study based on many ocean-bottom photographs and a large number of biological samples retrieved from the bottom close to the hulks reveals no visible damage to the marine ecology in DWD Area A. Based on these results and other tests performed, it was concluded that at the time of the survey no adverse impact on the marine environment could be attributed to the sunken hulks.

A SURVEY OF PROPELLANT, EXPLOSIVE AND PYROTECHNIC MATERIALS DISPOSED OF AT NAVORDSYSCOM FACILITIES AND SOLUTIONS TO POLLUTION AND RECOVERY PROBLEMS

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ABSTRACT

Surveys of PEP materials disposed of by burning as scrap or detonated in tests at NAVORDSYSCOM facilities have been conducted for the calendar years 1970-1972. General trends and specific problems have been identified by these surveys. The Naval Ordnance Systems Command has initiated R&D efforts aimed at eliminating these problems.

An introduction to planned new methods for disposal potentially available from recent research is given. This includes PBX removal, breakdown and recovery, biodegradation, and water-soluble binders for readily recoverable plastic bonded explosives.

EFFECTS OF SOIL AND WEATHER ON THE DECOMPOSITION OF EXPLOSIVES

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ABSTRACT

Twelve high explosive materials were buried in soil and exposed to the elements to determine their rate of disappearance from the environment. Tests have been conducted over an eight-year period and as of now only explosives that contain TNT, barium nitrate, and boric acid disappeared at a useful rate.

DESIGN OF HEAT-SENSITIVE BINDERS TO ENHANCE ORDNANCE DISPOSAL

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The method of disposal of ordnance after the operational period has passed must be safe, economical, and compatible with the environment. Current methods being studied elsewhere, such as solvent extraction, melting, or hydraulic removal, are a partial answer but they are sometimes not suitable for many formulations and hardware configurations. An explosive composition is needed that will allow for easy removal while assuring reliable performance.

Under the sponsorship of the Naval Ordnance Systems Command, Stanford Research Institute investigated present ordnance disposal systems and the feasibility of developing explosive compositions with inherent disposal characteristics. The objective of the program was to define structural modifications in ingredients, principally the binder, that would provide controlled degradation of the system for disposal by chemical or physical means. The study was conducted in two phases: the first phase established binder characteristics and evaluated theoretical approaches that would make the ingredients vulnerable to disposal methods and yet meet the operational requirements; the second was an experimental phase in which the results of the first effort were applied to practical systems to test feasibility. The scope of the study was limited to the present types of plastic-bonded explosives (PBXs) used by the Navy, and primary consideration was given to techniques that would facilitate removal from the casings.

During the first phase we considered five methods of controlling disposal of ordnance: (1) use of binders susceptible to decomposition upon demand by some energy input, (2) use of external attacking agents (other than solvents) to degrade the composition, (3) inclusion of a microencapsulated degradation

agent for later release to initiate degradation, (4) incorporation of inhibitors whose exhaustion could be controlled, and (5) use of inherently unstable binders that autocatalytically decompose after a controllable time interval. Only method (1), using a heat-sensitive binder, appeared to hold the promise of being nonpolluting, economical, and non exothermic, as required for disposal of ordnance.

A heat-sensitive binder decomposes on demand at a sufficiently rapid (~1 hr half-life) rate at a temperature somewhat above the desired maximum service temperature. Once a relatively small number of cleavages occur in the binder molecule structure (perhaps 1 per 5000 molecular weight), the binding properties are destroyed, facilitating both the removal of the explosives and the separation of the chemical components from one another. Thus, if the bond of the heat-sensitive group (-A-B-) that is broken upon decomposition is part of the polymer backbone of the binder, decomposition will give polymer cleavage.

$$\text{(Polymer)-A-B-(Polymer)} \rightarrow \text{(Polymer)-A} + \text{B-(Polymer)}$$

The desired amount of thermally labile groups that are needed for incorporation into an otherwise thermally stable polymer will be in the range of a few percent and could actually be built into the chain extender or perhaps into the crosslinking agent.

This concept has been theoretically evaluated to determine the temperatures necessary to decompose the heat-labile groups in a reasonable length of time and the kinetic parameters for the heat-labile groups that will give both stability at low temperature and instability at some elevated temperatures. On the basis of the kinetic parameters required, we selected candidate heat-sensitive groups.

The decomposition of the labile groups is limited to unimolecular processes since bimolecular processes present serious theoretical as well as practical application problems. The rate constant k for a unimolecular reaction may be expressed in the typical Arrhenius form

$$k = A \cdot 10^{-E_a/\theta} \quad \text{or} \quad \log k = \log A - E_a/\theta$$

where A is an entropy term, E_a is the activation energy of the reaction (kcal/mol), and $\theta = 4.6T \times 10^{-3}$. Thus from a value of k at one temperature and a value of A typical of the type of reaction of interest, E_a and the temperature dependence are fixed.

In general, the greater the number of heat-labile groups present in the binder, the smaller the fraction that need to decompose to cause a significant change in the properties of the binder. However, when the number of heat-labile groups corresponds to the number of crosslinking units, essentially all the groups must decompose to return the system to the originally viscous mixture before crosslinking. A 50% decomposition will probably be needed to reach a critical change in physical properties. This degree of decomposition corresponds to only a small fraction of the total binder system. As a conservative estimate of the amount of cleavage that will not alter the properties of the binder, we have used 10% of heat-labile groups or a loss comparable to 10% of the crosslinks. The amount of cleavage needed to eliminate the binding properties is assumed to be 50 to 90% of the heat-labile groups. This degree of decomposition would occur in slightly more than 1 to 3 half-lives of the heat-labile units.

The maximum service temperature for a binder depends generally on the application. However, a minimum safety test requirement of the Navy (WR-50) is based on no apparent physical change after a total of 14 days (336 hours) at 165°F (74°C). As discussed above, we have assumed that if there is to be no significant change in the binder properties during this time, there must be less than 10% decomposition of the heat-labile groups. Since the reaction of the labile groups X will be unimolecular, the following equation describes the decomposition:

$$d[X]/dt = k[X]$$

or upon integration

$$\ln[X]_o/[X] = k \cdot t$$

where $[X]_o$ is the initial value of $[X]$. At $[X]_o/[X] = 1.11$ (10% decomposition) with t equal to 336 hr (1.2×10^6 sec), k equals 8.6×10^{-8} sec^{-1}. This rate constant corresponds to the maximum possible rate constant if 10% decomposition of the heat-labile groups is not to be exceeded in the 165°F (74°C) test.

In Figure 1 log k is plotted versus 1/T according to the log form of the Arrhenius rate expression. The dashed line corresponds to rate constants for decomposition of heat-labile groups where 10% decompose in 336 hours at 75°C (assuming $A = 10^{14}$ sec^{-1}). Changing **A** by a factor of 10^2 has only a small effect on this line. The value of E_a is 33.4 kcal/mole; if $A = 10^{16}$, $E_a = 36.6$, and if $A = 10^{12}$, $E_a = 30.3$. From Figure 1, the temperature required to obtain 50% decomposition of the heat-labile groups in 1 hour (1 half-life) is 139°C. The temperature required for 50% decomposition in 10 hours is 120°C. Thus, binders that are stable at 25 and 74°C could be decomposed in a reasonable length of time (about 1 hr) at ~140°C, which is within the temperature range where HMX and RDX are stable.

We have found several functional groups that decompose at rates in the range of interest. Lines for several possible exemplary compounds, mostly azo compounds, are plotted in Figure 1. The decomposition of phenylazodiphenylmethane [$PhN_2CH(Ph)_2$] falls close to the calculated line. The decompositions of azotoluene ($PhCH_2N_2CH_2Ph$) and azoisobutane (t-BuN_2-t-Bu) fall somewhat below; azoisopropane (i-PrN_2-i-Pr) is considerably more stable than necessary.

During the second phase of the study, an experimental program was undertaken to examine the use of azo linkages in a model binder to test concepts developed in the first phase. Azobisisobutanol, $HOCH_2C(CH_3)_2N{=}NC(CH_3)_2CH_2OH$, which was anticipated to decompose at a rate similar to that for azoisobutane (shown in Figure 1), was prepared according to a literature route and endcapped with toluene diisocyanate. This material was chain-extended with polypropylene glycol

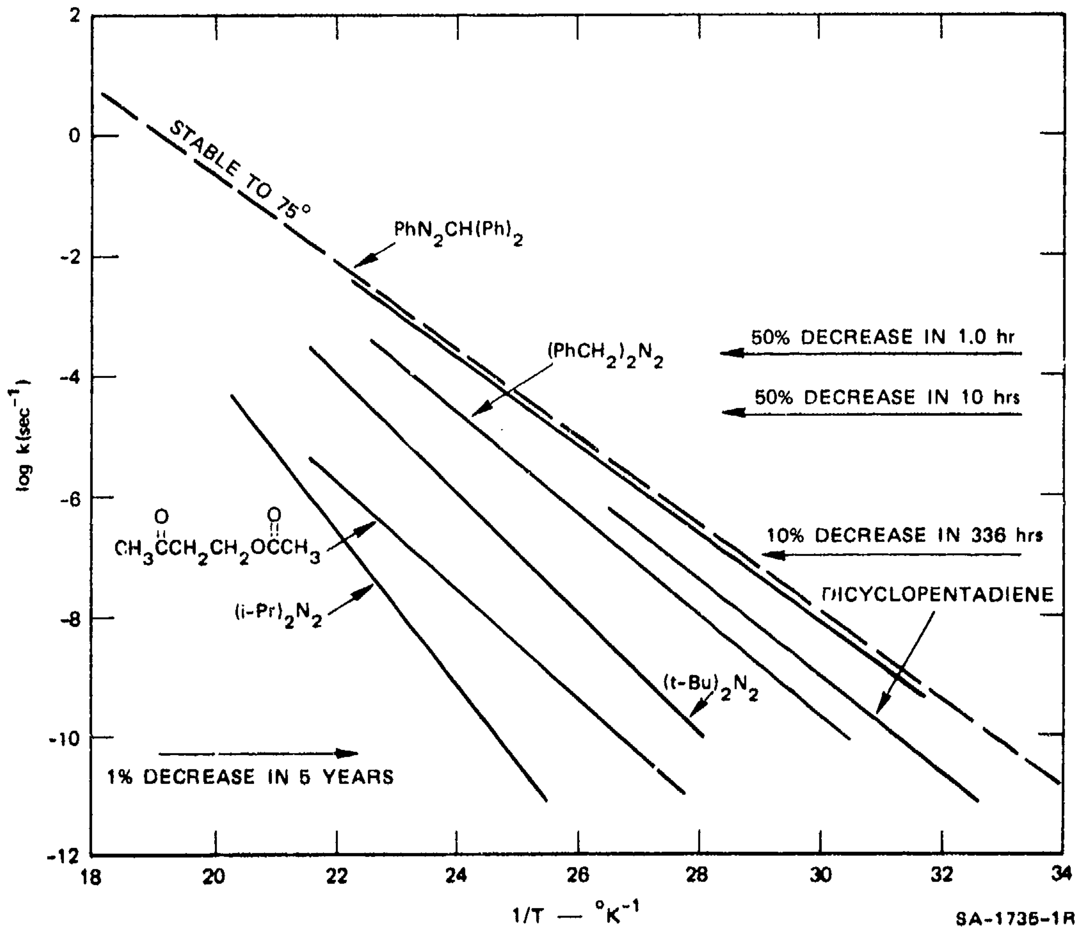

FIG. 1 ARRHENIUS PLOTS FOR BINDERS THAT ARE STABLE TO 75°C AND SOME REPRESENTATIVE HEAT-SENSITIVE GROUPS

(MW = 2000) and cured with ethylenediamine to give a white, elastomeric polymer. The polymer was subjected to the temperature and time requirements (185°C, 2 hr) predicted to cause decomposition of the azo linkage. Indeed, under these conditions the polymer changed from a rubbery solid to a liquid that remained fluid but viscous at room temperature. A similar polymer without azo units showed no significant change when treated in a similar manner. During the decomposition of the azo-containing polymer, the rate of nitrogen evolution was consistent with the composition of the polymer and the kinetics of this azo compound.

A second experimental polyurethane, containing the heat-sensitive azo linkage, was prepared and cured with 1,4-butanediol. This rubbery, diol-cured polymer also reverted to a viscous liquid on heating at 160 and 185°C. Likewise, the amount of nitrogen evolved at these temperatures gave first-order rate constants comparable to literature values for similar azo compounds and comparable also to the results obtained on heating of the amine-cured polyurethane.

Thus, polyurethanes containing heat-sensitive azo linkages are practical binder-systems that, after further study, could be used to facilitate disposal of ordnance. Work continues on the preparation of other heat-sensitive groups that can be incorporated into binders with emphasis on new heat-sensitive groups that will decompose in 1 hr in the temperature range of 130 to 150°C.

ENVIRONMENTAL STUDIES AT S-SITE - WATER AND SOIL ANALYSES
FOR RDX-HMX, BARIUM, TNT, AND BORON

Andrew Turner

LOS ALAMOS SCIENTIFIC LABORATORY

ABSTRACT

Overall studies were made to determine the level of RDX-HMX, barium, TNT, and boron contamination occurring in S-Site* effluent, to determine the concentration of these elements and compounds that have built up in the soil, and to determine the source and travel distance of these materials throughout the S-Site drainage system. Methods of analyses for RDX-HMX, TNT, barium, and boron in water and soil are discussed.

* An ordnance plant.

Products Resulting From Microbiological Degradation of Alpha-Trinitrotoluene

by

John C. Hoffsommer, Donald J. Glover, Michael Sitzmann, and Donald A. Kubose

The isolation of 4-amino-2,6-dinitrotoluene (1) and 2-amino-4,6-dinitrotoluene (2) from stream waters near a bomb loading facility at NAD, McAlester, Oklahoma indicated that alpha-trinitrotoluene could be biodegraded. These and other biodegradation products of alpha-trinitrotoluene were isolated, identified, and analysed at NOL by a combination of thin-layer and vapor-phase chromatography, together with visible spectrophotometry and in some cases mass spectrometry. For further verification, these isolated compounds were compared to independently synthesized compounds.

Under a contract to NOL, C. A. Hudock and L. M. Gring at the University of Indiana were able to biodegrade alpha-trinitrotoluene in the laboratory with pure strains of bacteria. After biodegradation aqueous solutions were sterilized and sent to NOL for analyses. The bacterial strain, E. Coli, for example, in a supplemented glucose media was found to metabolize alpha-trinitrotoluene to (1) in a 28% molar conversion with no detectable formation of (2). The pseudomonas fluorescens, bacterial strain, on the other hand, completely metabolized alpha-trinitrotoluene, but only a 0.5% conversion to a mixture of (1) and (2) were formed.

Recently, R. J. Heckly and W. D. Won at the Naval Biomedical Research Laboratory (NBRL), Berkeley, California were able to biodegrade alpha-trinitrotoluene with bacteria isolated from soil samples obtained from the same streams where the formation of (1) and (2) were first observed. Of over sixteen bacterial types, three yellow pigment producting organisms were isolated and identified as belonging to the genus pseudomonas, designated as isolates I, II, and Y which were found

to most actively metabolize alpha-trinitrotoluene.

Experiments were subsequently conducted at NOL with Dr. Orin H. Halverson, as consultant, with the objective of obtaining data for the design of an oxidation ditch for the large-scale biodegradation of alpha-trinitrotoluene. The ditch would be inoculated with a mixed strain of bacteria found in the activated sludge from domestic sewage treatment facilities and would be fed additional nutrient such as corn steep liquor, black strap molasses, or stick liquor.

Curves for the biodegradation of aqueous alpha-trinitrotoluene with activated sludge and isolate Y from NAD, McAlester, Oklahoma are shown in graph 1. After 72 hours, 96% of the alpha-trinitrotoluene was biodegraded with the bacterial isolate, Y, while 93% was degraded in 62 hours using the activated sludge mixed cultures. Both biodegradations used glucose as an additional nutrient in a ratio of about 10/1 for glucose/alpha-trinitrotoluene. Cultures for isolate Y were inoculated in 100 ml aqueous solutions under shaking conditions in a 250 ml erlenmyer flask to which had been added 0.2 ml of a 50% sterile glucose solution followed by 1.0 ml of inoculum (24 hour growth of isolate Y in 0.1% peptone glucose broth at 32 C under shaking conditions). For the activated sludge biodegradation, 15 liters of 100 ppm alpha-trinitrotoluene was mixed with 5 liters of activated sludge having a biological oxygen demand of 3,000 to 5,000 ppm. Sufficient glucose, glutamic acid and sodium bicarbonate were then dissolved in this solution to make the final concentration of each 500 ppm. At hourly intervals between 20 and 25 hours, one liter of the 20 liter mixture was removed, while one liter of 100 ppm alpha-trinitrotoluene was added in its place. The rate of the activated sludge biodegradation remained reasonably constant at ~4 ppm alpha-trinitrotoluene/hour during this period and was similar to the biodegradation of alpha-trinitrotoluene with isolate Y.

In addition to (1) and (2) which were found with isolates I, II, Y and activated sludge mixed cultures, table 1, nitrite (3) and nitrate (4) ions were found in a combined yield of 3% based on the amount of alpha-trinitrotoluene biodegraded. The ratio of nitrite/nitrate averaged 4.0 for the three isolates, I, II, and Y. The pH was observed to increase with time during biodegradation, table 1.

Products (1), (2), (3), and (4) were identified as coming from the aqueous phase after alpha-trinitrotoluene biodegradation. Two additional compounds in a combined yield of 1.7% were isolated from the acetone extracts of the bacterial floc. These compounds were identified as the 3,3',5,5'-tetranitro-4,4'-dimethylazoxybenzene (5) and 3,3',5,5'-tetranitro-2,2'-dimethylazoxybenzene (6) by thin-layer chromatography, visible spectrophotometry with ethylenediamine-dimethylsulfoxide complexes of the compounds, and mass spectrometry, table 2. Two additional compounds were observed with similar R_f values to (5) and (6) and at the same time produced similar purple colored complexes on thin-layer chromatographic plates with ethylenediamine-dimethylsulfoxide spray. These compounds are most likely the mixed azoxy compounds: 3,3',5,5'-tetranitro-2,4'-NNO-dimethylazoxybenzene (7) and the 3,3',5,5'-tetranitro-2',4-NNO-dimethylazoxybenzene (8). One of these compounds has been isolated from thin-layer chromatographic plates after two dimensional development and gives a parent ion of 406 (M/e = molecular weight) and a similar mass spectrum to (5) and (6) in the mass spectrometer.

Although not identified or isolated, it is most likely that the (5), (6), (7) and (8) coupled products arise from coupling reactions between 4,6-dinitro-2-hydroxylaminotoluene (9) and 2,6-dinitro-4-hydroxylaminotoluene (10). In this regard, an aqueous solution of (10) will precipatitate the symetrically coupled (5) on standing overnight. Similarly, the symetrically coupled product (6) would be expected to be formed from (9) while the unsymetrically coupled azoxy pro-

ducts would be expected to be formed from reactions between (9) and (10).

Experiments are now underway at NOL to optimize the parameters for microbiological degradation of alpha-trinitrotoluene as well as to minimize nitro containing by-products. Results from these experiments will provide necessary input for NOL's nearly completed oxidation ditch for large-scale alpha-trinitrotoluene biodegradation.

Glossary

1. 4-amino-2,6-dinitrotoluene.
2. 2-amino-4,6-dinitrotoluene.
3. nitrite ion.
4. nitrate ion.
5. 3,3',5,5'-tetranitro-4,4'-dimethylazoxybenzene.
6. 3,3',5,5'-tetranitro-2,2'-dimethylazoxybenzene.
7. 3,3',5,5'-tetranitro-2,4'-NNO-dimethylazoxybenzene.
8. 3,3',5,5'-tetranitro-2',4-NNO-dimethylazoxybenzene.
9. 4,6-dinitro-2-hydroxylaminotoluene.
10. 2,6-dinitro-4-hydroxylaminotoluene.

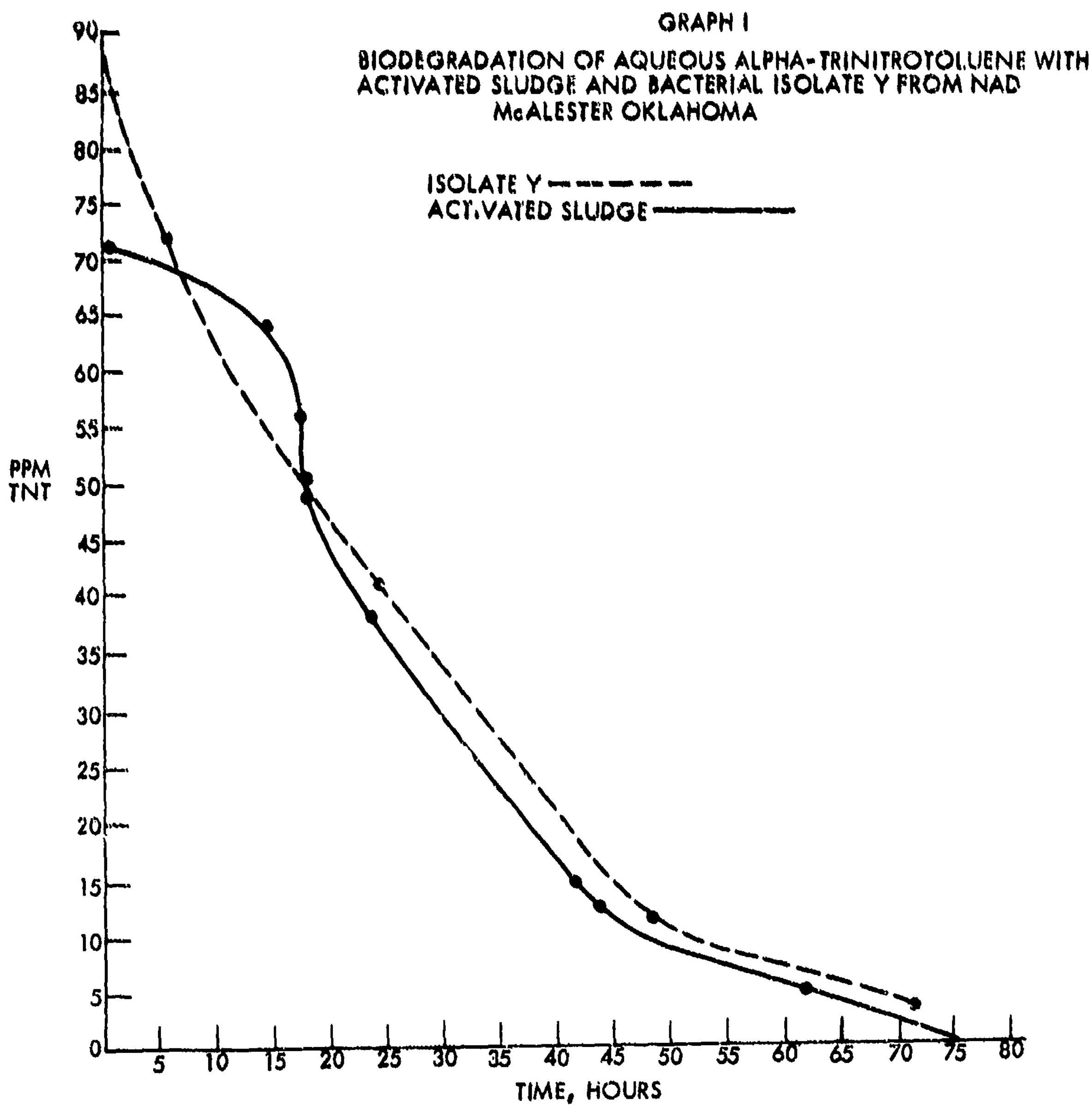
GRAPH I
BIODEGRADATION OF AQUEOUS ALPHA-TRINITROTOLUENE WITH ACTIVATED SLUDGE AND BACTERIAL ISOLATE Y FROM NAD McALESTER OKLAHOMA
ISOLATE Y
ACTIVATED SLUDGE
PPM TNT
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
TIME, HOURS

TABLE 1

INTERMEDIATE FORMATION OF 4-AMINO-2,6-DINITROTOLUENE (1) AND 2-AMINO-4,6-DINITROTOLUENE (2) IN THE BIODEGRADATION OF TNT

% TNT Biod.*	ppm	pH	ppm (1)	ppm (2)	Bacterial Isolate
55.5	49.2	3.10	5.8	5.2	I
89.4	79.3	6.65	6.4	5.8	I
97.5	86.5	6.89	13.8	6.1	I
65.7	58.3	3.15	7.9	6.7	II
87.5	77.6	7.15	7.1	3.2	II
95.6	84.9	6.19	9.7	5.9	II
53.4	47.3	3.13	4.2	4.2	Y
87.8	77.9	7.15	10.1	4.7	Y
95.8	85.0	6.89	14.1	5.2	Y
70.5	-	7.70	0.46	0.61	Activated Sludge

* 88.7 ppm alpha-trinitrotoluene at start.

TABLE 2

INTERMEDIATE FORMATION OF 3,3',5,5'-TETRANITRO-4,4'-DIMETHYLAZOXYBENZENE (5) AND 3,3',5,5'-TETRANITRO-2,2'-DIMETHYLAZOXYBENZENE (6) IN THE BIODEGRADATION OF ALPHA-TRINITROTOLUENE

% TNT Biod.	ppm (5)	ppm (6)
55	0.51	0.27
73	0.57	0.40

Biological Degradation of Trinitrotoluene

W. Won and R. J. Heckly

Naval Biomedical Research Laboratory
School of Public Health, University of California, Berkeley

The increasing concern for our environment has made it incumbent upon us to dispose of nothing but water into streams and lakes. Relatively large volumes of water containing dissolved exposives are being discharged from certain operations at Naval facilities. The "pink water", which is a result of air and sunlight on trinitrotoluene (TNT), has dramatically called attention to this problem of water pollution. A reason for considering bacteria to purify these waste waters is that the concentration of TNT is relatively low. A saturated solution of TNT contains less than 120 μg/ml. Fortunately, under proper conditions, bacteria can grow in media having a low nutrient level and it should be possible to operate a biological disposal system economically.

Samples of mud and water from each of 15 locations at NAD McAlester, Oklahoma were collected and organisms were isolated from these by an enrichment technique. In the initial screening a large number of organisms were isolated in pure culture that could grow in TNT solution, but only the three most promising were studied in detail. These have been designated as isolate Y, I and II, and tentatively identified as belonging to the genus Pseudomonas. Attempts to isolate other organisms has continued and recently another organism was isolated which utilizes TNT and grows even more rapidly than the other isolates.

A respirometric technique using a Warburg apparatus was used to evaluate the potential for TNT oxidation. With TNT the oxygen uptake was 23% higher than for the control containing only the basal salts. The increased rate of oxygen uptake, compared to the endogenous rate, with TNT added was not as great as that obtained with other substrates such as glucose, but because the method is sufficiently precise, these results are significant. It was on the basis of such measurements that the first three cultures were originally selected for study.

Measurements of growth rates and TNT degradation was done in 250 ml erlenmyer flasks with 100 ml of media per flask. The flasks were incubated at 30-32 C on a shaker at 200 rpm and were inoculated with 1 ml of a culture in peptone-glucose broth. Viability was assayed by plating 0.1 ml of appropriate dilutions on nutrient agar containing 0.5% glucose. Inoculated plates were incubated for 24 hr at 35 C. Typical results obtained are shown in Fig. 1. In this instance, the various materials were added to basal media containing 100 μg/ml TNT. Of the substances tested,

glucose best supported growth of all three strains. The optimum pH appears to be near 6.4 and at pH above 8 or below 5 none of the organisms survived well. Figure 2 shows the degradation of TNT that has been observed in a batch system using isolate I, but essentially the same data was obtained with Isolate II and Y. In this experiment, 6 replicate flasks containing 5×10^{-3} M glucose and about 4×10^{-4} M TNT were inoculated and incubated at about 30 C. At selected intervals, one flask was removed for analysis and slight variability from flask to flask may account for some of the irregularities in the curves. The loss of viability was probably due to acid produced from the glucose, but despite the low number of cells, the TNT degradation was essentially complete in 72 hr. It is of interest to note that the concentration of the intermediates, 6-dinitro-4-aminotoluene and 2 amino-4,6-dinitrotoluene plus the nitrite and nitrate failed to account for all of the TNT degraded. We now have evidence that in order to eliminate the residual intermediates, particularly the 6 dinitro-4-aminotoluene, one needs to add a nitrogen source such as yeast extract.

Since a batch system is not practical for treating wastes, studies have been extended to include a continuous culture system. Some preliminary tests were made using a small apparatus that has several inlets so that up to 3 media constituents can be added separately at any selected rate. The culture volume of the vessel is about 50 ml and a high aeration rate is obtained by passing the sterile air through a sintered glass sparger unit submerged in the culture.

Figure 3 summarizes some results that have been obtained using isolate I. In this experiment, the 100 μg/ml TNT solution was pumped in at 5 ml/hr and supplemented with 0.5% yeast extract, also at 5 ml/hr. The pH control was not activated since this was intended primarily as the baseline or point of departure for more refined studies. This indicates that about $< 10^{10}$ cells could degrade 100 μg TNT per hr and I believe that under optimal conditions and with pH control the rate can be increased significantly.

We have not yet determined why there were fluctuations in pH and viability in a supposedly steady state system. Nevertheless the prospects for developing a practical system to dispose of waste TNT solutions are good.

Acknowledgements

Our sincere thanks to Mrs. Cheryl Wang for her skillful technical assistance, and to Dr. John Hoffsommer, NOL, White Oak, Silverspring, Maryland for chemical analyses.

This work was sponsored by the Naval Ordnance Systems Command through a contract between the Regents of the University of California and the Office of Naval Research.

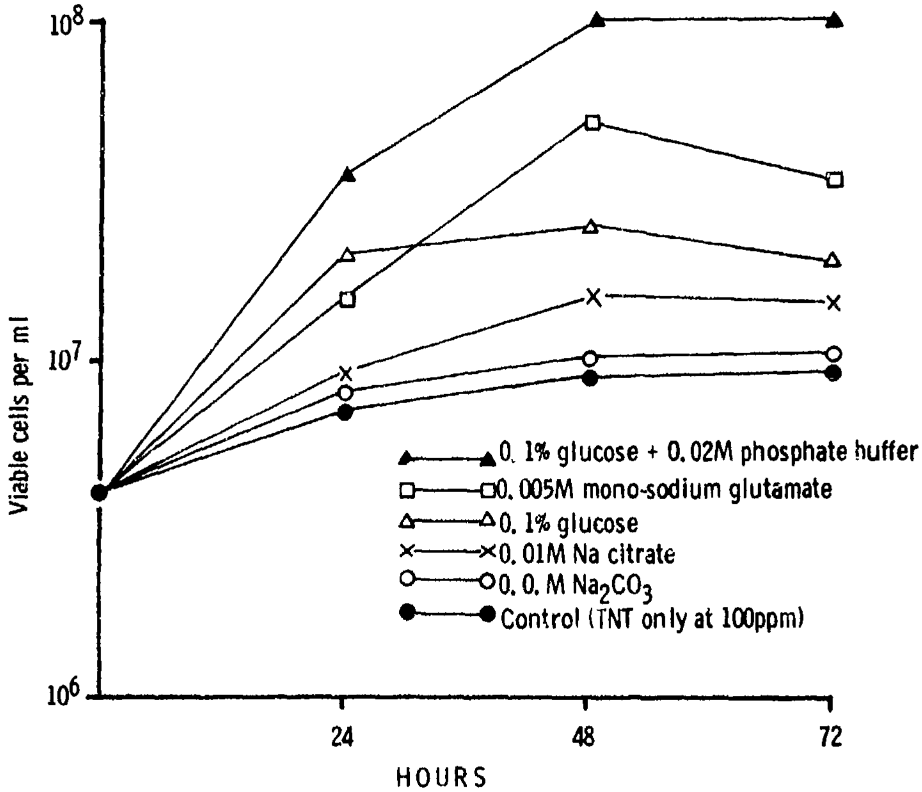

FIG. 1 GROWTH OF ISOLATE "I" IN FORTIFIED TNT MEDIA

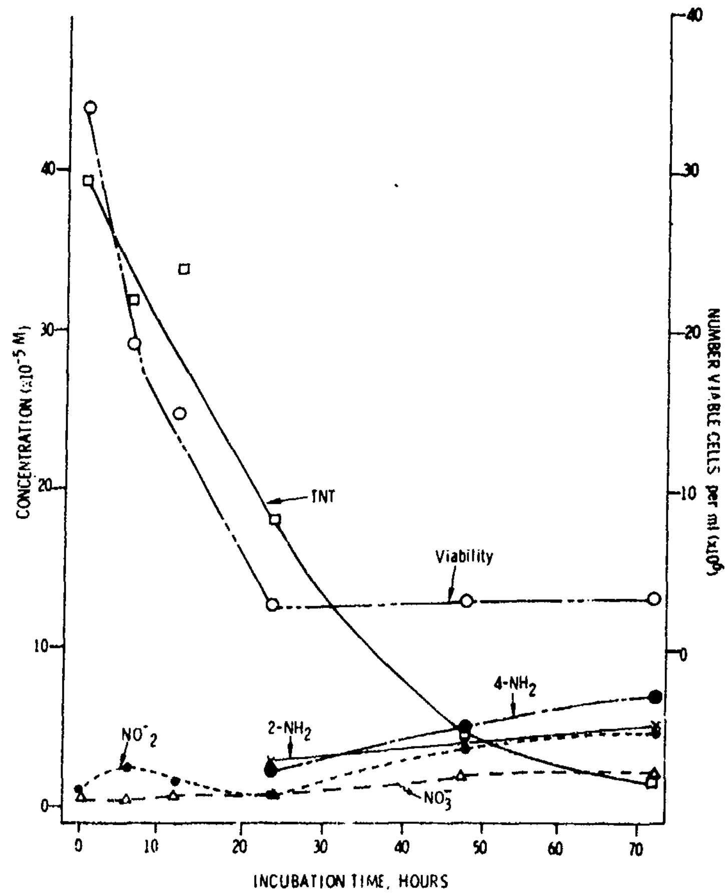

FIG. 2 EFFECT OF ISOLATE "Y" ON TNT SOLUTION 0.005 M GLUCOSE. 4-NH$_2$ = 2,6-DINITRO-4-AMINOTOLUENE 2-NH$_2$ = 2-AMINO-4,6-DINITROTOLUENE

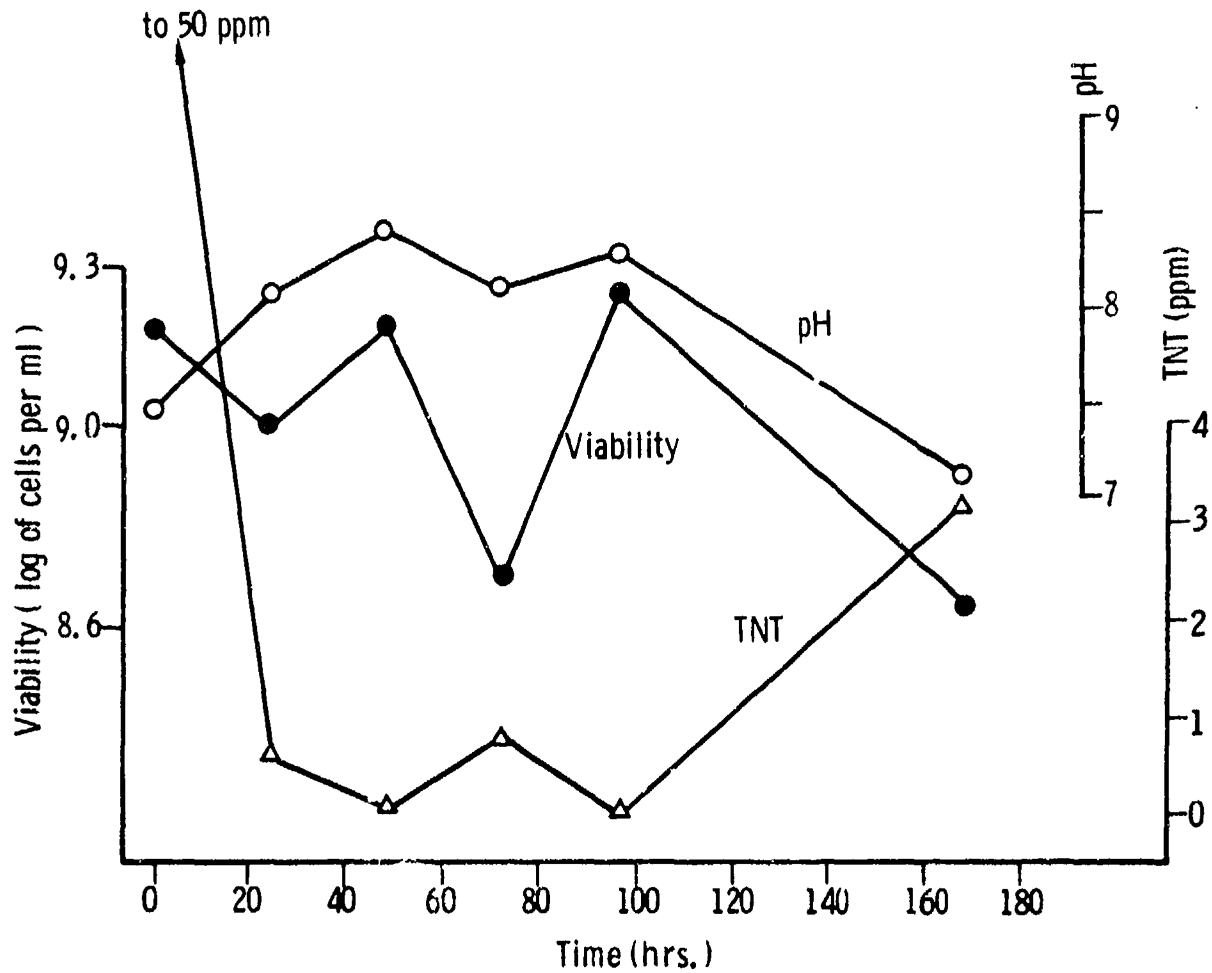

FIG. 3 RESULTS OF A CONTINUOUS CULTURE OF ISOLATE "I". SOLUTIONS 0.5% YEAST EXTRACT AND 100 PPM TNT WERE EACH ADDED AT 0.1 VOLUME PER HR.